STATE OF CALIFORNIA
DEPARTMENT OF TRANSPORTATION
DIVISION OF FACILITIES CONSTRUCTION
OFFICE OF TRANSPORTATION LABORATORY

CALIFORNIA PCC PAVEMENT FAULTING STUDIES: A SUMMARY

Study Made by .... Pavement Branch

Under the Supervision of .... R. A. Forsyth, P.E. and R. N. Doty, P.E.

Principal Investigators .... J. H. Woodstrom, P.E. and L. R. Ferroni, P.E.

Co-Investigator .... B. F. Neal, P.E.

Report Prepared by .... B. F. Neal, P.E.

RAYMOND A. FORSYTH, P.E.
Chief, Office of Transportation Laboratory

85-06

90-58

TECHNICAL REPORT STANDARD TITLE PAGE

1. REPORT NO. FHWA/CA/TL-85/06

2. GOVERNMENT ACCESSION NO.

3. RECIPIENT'S CATALOG NO.

4. TITLE AND SUBTITLE CALIFORNIA PCC PAVEMENT FAULTING STUDIES: A SUMMARY

5. REPORT DATE December 1985

6. PERFORMING ORGANIZATION CODE

7. AUTHOR(S)
B. F. Neal

8. PERFORMING ORGANIZATION REPORT NO. 54-633366

9. PERFORMING ORGANIZATION NAME AND ADDRESS
Office of Transportation Laboratory
California Department of Transportation
Sacramento, California 95819

10. WORK UNIT NO

11. CONTRACT OR GRANT NO. F81TL22

12. SPONSORING AGENCY NAME AND ADDRESS
California Department of Transportation
Sacramento, California 95807

13. TYPE OF REPORT & PERIOD COVERED Interim

14. SPONSORING AGENCY CODE

15. SUPPLEMENTARY NOTES
This study was conducted in cooperation with the U.S. Department of Transportation, Federal Highway Administration, under the research project entitled "Evaluation of Experimental PCC Construction."

16. ABSTRACT
A summary of the findings from several California Department of Transportation studies of faulting since 1968 is presented. Causes of faulting were discovered and mitigation measures developed. These measures have been implemented on new construction projects, but some experimentation is still going on for retrofitting older projects.

17. KEY WORDS
Concrete bases, concrete pavements, drainage, faulting, grout injection, pavement pumping.

18. DISTRIBUTION STATEMENT
No restrictions. This document is available to the public through the National Technical Information Service, Springfield, VA 22161.

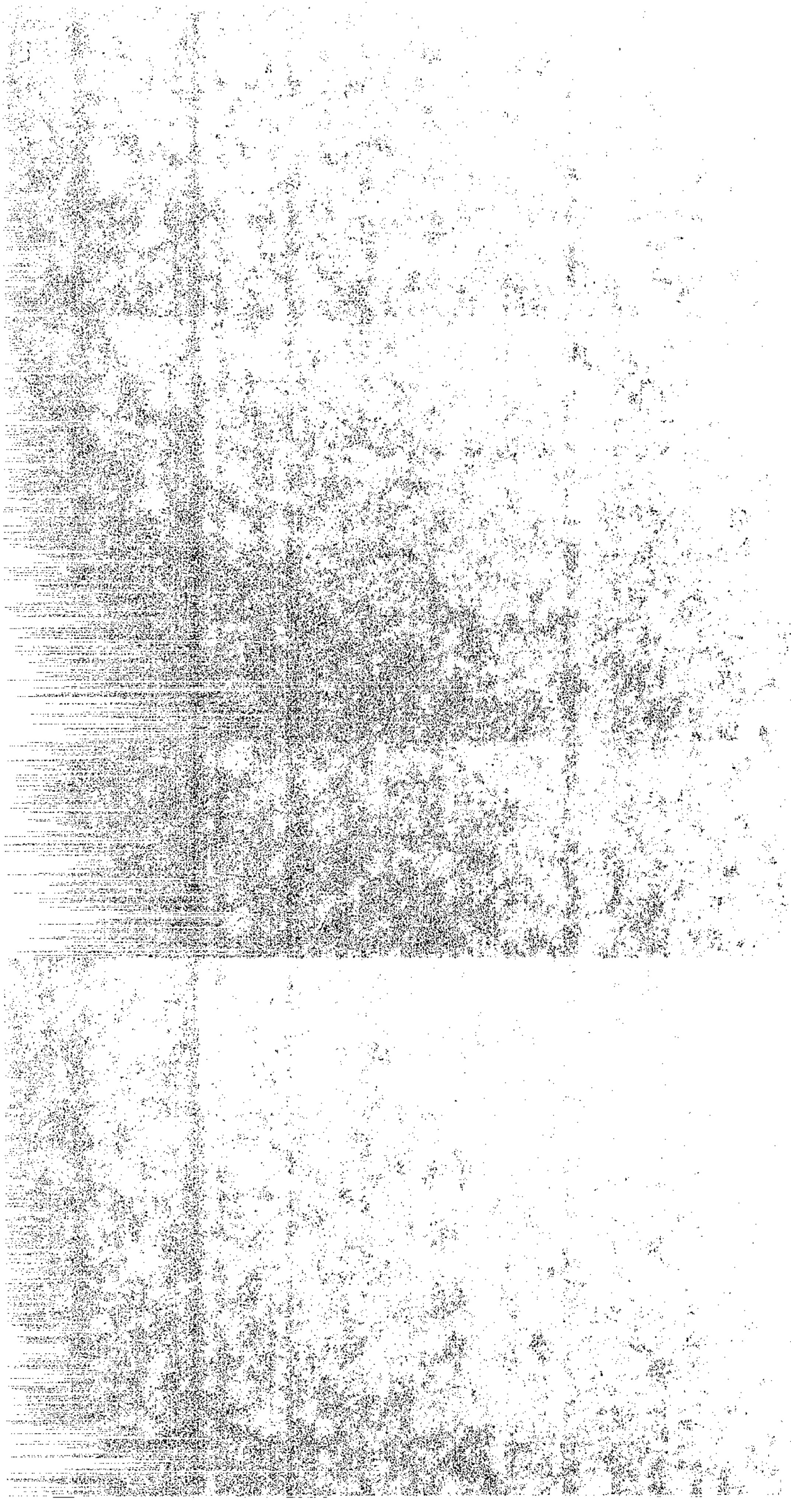
19. SECURITY CLASSIF. (OF THIS REPORT)	20. SECURITY CLASSIF. (OF THIS PAGE)	21. NO. OF PAGES	22. PRICE
Unclassified	Unclassified		

DS-TL-1242 (Rev.6/76)

NOTICE

The contents of this report reflect the views of the Office of Transportation Laboratory which is responsible for the facts and the accuracy of the data presented herein. The contents do not necessarily reflect the official views or policies of the State of California or the Federal Highway Administration. This report does not constitute a standard, specification, or regulation.

Neither the State of California nor the United States Government endorse products or manufacturers. Trade or manufacturers' names appear herein only because they are considered essential to the object of this document.



CONVERSION FACTORS

English to Metric System (SI) of Measurement

Quality	English unit	Multiply by	To get metric equivalent
Length	inches (in)or(")	25.40 .02540	millimetres (mm) metres (m)
	feet (ft)or(')	.3048	metres (m)
	miles (mi)	1.609	kilometres (km)
Area	square inches (in^2) square feet (ft^2) acres	6.432×10^{-4} .09290 .4047	square metres (m^2) square metres (m^2) hectares (ha)
Volume	gallons (gal) cubic feet (ft^3) cubic years (yd^3)	3.785 .02832 .7646	litre (1) cubic metres (m^3) cubic metres (m^3)
Volume/Time (Flow)	cubic feet per second (ft^3/s	28.317	litres per second 1/s)
	gallons per minute (gal/min)	.06309	litres per second (1/s)
Mass	pounds (lb)	.4536	kilograms (kg)
Velocity	miles per hour (mph) feet per second (fps)	.4470 .3048	metres per second (m/s) metres per second (m/s)
Acceleration	feet per second squared (ft/s^2)	.3048	metres per second squared (m/s^2)
	acceleration due to force of gravity (G) (ft/s^2)	9.807	metres per second squared (m/s^2)
Density	(lb/ft^3)	16.02	kilograms per cubic metre (kg/m^3)
Force	pounds (lbs). (1000 lbs) kips	4.448 4448	newtons (N) newtons (N)
Thermal Energy	British termal unit (BTU)	1055	joules (J)
Mechanical Energy	foot-pounds (ft-lb) foot-kips (ft-k)	1.356 1356	joules (J) joules (J)
Bending Moment or Torque	inch-pounds (in-lbs) foot-pounds (ft-lbs)	.1130 1.356	newton-metres (Nm) newton-metres (Nm)
Pressure	pounds per square inch (psi)	6895	pascals (Pa)
	pounds per square foot (psf)	47.88	pascals (Pa)
Stress Intensity	kips per square inch square root inch (ksi$\sqrt{in}$)	1.0988	mega pascals$\sqrt{metre}$ (MPa$\sqrt{m}$)
	pounds per square inch square root inch (psi$\sqrt{in}$)	1.0988	kilo pascals$\sqrt{metre}$ (KPa$\sqrt{m}$)
Plane Angle	degrees (°)	0.0175	radians (rad)
Temperature	degrees fahrenheit (F)	$\frac{+F - 32}{1.8} = +C$	degrees celsius (°C)

TABLE OF CONTENTS

BACKGROUND

For a number of years, highway research engineers in California have been studying the problem of faulting of jointed PCC pavements*. Several reports(1,2,3,4) document the findings of this research. The cause of faulting was found to be the buildup of fine material under slabs at the approach side of transverse joints. This buildup is due to the pumping action caused by loaded trucks depressing curled slabs when water is present under the pavement. This conclusion was verified by placing tracer sands under the pavement and in the shoulder area, then later lifting the slabs and locating the different sands. The sources of the fines were found to be the adjacent shoulder and the base surface when eroded by the pumping action.

To prevent faulting, the combination of contributing factors must be eliminated. Preventing the entry of all water through joints and cracks is not considered feasible. A joint sealant system to provide watertight seals year-round and over a period of years has not been developed. While joint seals do not keep out all water, they do help prevent the entry of detrimental fine materials. To eliminate the free water factor, however, drainage must be provided.

The problem of slab deflections at joints due to heavy wheel loads over curled slabs is even more difficult to solve. While dowels across joints would be expected to improve load transfer, the long term performance and high cost of installation make it difficult to justify their use in California. The use of a lean concrete base or cement

---

*The term "faulting", as used in this report, refers to the vertical displacement of concrete pavement slabs at joints.

treated base provides a "non-erodible" foundation capable of supporting the pavement slabs under the heaviest loads using only aggregate interlock at the contraction joints.

For more than 30 years, California used cement treated base (CTB) to provide "non-erodible" support for the pavement slabs. While the quality of this base has been upgraded periodically, the surface is still erodible to some degree. Under typical base construction practice, excess material is placed, compacted, trimmed to grade, then recompacted. The material loosened by trimming is often not properly recompacted due to partial hydration of the cement, or other reasons. Also, the asphalt curing membrane usually penetrates the base to some extent, and also adheres to the pavement slabs. As the slabs curl upward, the membrane often pulls loose from the base, bringing some particles upward with it and leaving other loose particles exposed to the pumping action. More recently, bases constructed of lean concrete(5) or asphalt concrete(6) have been found to be satisfactory and much more resistant to abrasion. This is one of the reasons for the subsequent adoption of lean concrete base (LCB) to replace CTB as the California Department of Transportation (Caltrans) standard base material for rigid pavements.

Untreated base material typically used in shoulder construction was found to also be a major source of the fines found under faulted slabs. To prevent faulting, this source must be eliminated. Proposed methods included stabilizing the portion of the outer shoulder adjacent to the slab with asphalt or cement or isolating the material from the slab by use of a filter fabric.

Evaluating the effectivenss of various mitigation measures by observing performance in the field requires a number of years. To speed up this evaluation, a research project was initiated to conduct an accelerated testing program(4). The project included construction of a model structural section in the laboratory complete with two concrete pavement slabs. Equipment was installed to provide timed cyclic loadings on each side of a joint to simulate moving wheel loads. Heat was provided under the slabs to help induce curl, and water was made available to provide a medium for transporting loose fine material.

This study verified previous findings regarding the factors involved in faulting. Faulting was induced on the model slabs under laboratory-controlled conditions of free water, available fines, and loads applied to slabs which were curled upward. After techniques were developed, significant faulting (0.02 inch or more) could be built up within a month. This provided an opportunity to test several different mitigation measures.

From observations made while loading was in progress and also when the slabs were raised for purposes of inspection, the pumping pattern was found to vary considerably in direction, but generally was in a semi-circular pattern. Movement of fines started from the shoulder on the leave side of the joint, went under the slab, across the joint, then towards the outer shoulder on the approach side. When a void area was built into the approach shoulder, such as a drainage pipe or permeable material, the fines would fill all those voids, then be redirected to another spot. Filter fabric placed along the edge would become plugged and ineffective in allowing water to move through.

Similar plugging of drains in field installations created some concern. However, methods were developed to flush the systems and cleanout facilities are now provided for these drainage features.

The need for a more erosion resistant base than CTB was also verified. Lean concrete and dense graded asphalt concrete have been found to be superior to CTB in this regard and are now being specified for most projects. Two other products have now been accepted as a substitute for CTB. These are asphalt treated permeable base (ATPB) and cement treated permeable base (CTPB). These products consist of coarse aggregate and either 1-1/2 to 2% asphalt or 282 lbs/CY of portland cement. These materials serve the dual purpose of providing both drainage and a nonerodible base.

Several recommendations that were expected to result in improved performance were made as a result of the faulting research. On new PCC construction projects, an erosion resistant base, as described above, was recommended and a drainage facility for the outside shoulder area adjacent to the slab was also recommended to remove the water collected in the permeable base layer. The recommended drainage facility consisted of slotted pipe covered with permeable material, preferably cement or asphalt treated, with filter fabric protecting the permeable material from contamination by the adjacent untreated material. Pipe outlets (non-slotted) were recommended as well as provision for flushing in case the drains become plugged.

For pavements previously built without the above recommended protection, retrofit edgedrain systems were recommended. They serve to remove water and prevent the intrusion of additional fines. Another recommendation was that the fines already under the slabs be immobilized. This was to prevent the fines ejected into the shoulder during the pumping action from plugging the drainage system. Although no method of immobilizing the fines was then available, the need to develop a method was considered highly desirable. Subsealing with silicone foam was developed to effectively prevent water and fine movement.

CONCLUSIONS

The factors involved in faulting were found to be: 1) free water under the slabs; 2) deflection of slabs under heavy moving wheel loads; and 3) unstabilized or erodible material under or adjacent to the slabs. To prevent faulting, a nonerodible base is necessary, as well as a drainage system in the shoulder area containing slotted pipe and treated permeable material. This drainage system must be protected from infiltration by untreated fine material. On existing faulted pavements, an edgedrain system should be installed, and stabilizing the fines already under the slabs is desirable. The injection of a closed-cell silicone foam is effective in preventing pumping and further movement of fines.

IMPLEMENTATION

Specifications are already in effect in California requiring nonerodible bases and drainage facilities on new construction projects. On existing PCC projects, drainage is being installed as funds permit. Methods of stabilizing existing fines under slabs are still being studied but adoption of subsealing with an impermeable foam is being encouraged. Although relatively expensive, the injection of silicone foam should be a cost-effective alternative on retrofit projects where a drainage system is not feasible.

SLAB INJECTION STUDY

Mud-jacking, or the injection of grout under the pavement, has long been used to raise sunken slabs and to fill voids. If a similar material were to be used under faulted pavements, it would need to be erosion resistant. On checking grouts used around the state, the quality was found to be quite variable with most mixes having little strength, especially at early ages. After further testing, a standard grout mix design was adopted, consisting of approximately one part cement to three parts pozzolan. This resulted in considerable strength improvement, though still not considered a nonerodible material. Being a rigid material when set, this grout becomes a new base for the pavement, establishing a new zero point from which curling and faulting can resume. This action is a result of the plastic nature of concrete pavements that yield by plastic flow or "creep" under sustained or long-term loading, such as a propped cantilever slab.

Experiments were made with a chemical grout injected under test slabs in the laboratory(4). This appeared to work reasonably well as long as there was moisture available to the grout. When the moisture was gone, the grout became brittle and disintegrated under cyclic loading.

Other materials tried under the test slabs were polyurethane and silicone rubber foam. The polyurethane was an open-cell product which readily became saturated with water and fines and disintegrated after a fairly short time. The silicone rubber foam was a two-component product which expanded to approximately three times its original volume as a closed-cell (about 95%) foam. The viscosity of the original sample was too high for rapid injection, and the setting time was too fast. The manufacturer, General Electric Company, assisted in modifying the material to accommodate these needs. Silicone oil was added to reduce the viscosity, and a retarder furnished so that the setting time could be increased to about five minutes at room temperature. This modified material was then injected through the faulted model slab near the joint on the leave side. The injection proceeded smoothly and was stopped when the slab started to rise from the expansion of the foam.

Cyclic loading began shortly after injection and continued for over three months, accumulating almost 3,000,000 cycles. During this time, water was periodically made available, fines were present in the shoulder, and curl was induced several times. None of the fines in the shoulder area were moved, the water being drained was clear, and no signs of pumping could be detected. When the slab was raised for inspection, the foam was in place, well distributed under the slab, but in varying thicknesses according to the size of the voids. No deterioration of the foam had taken place. The results exceeded all expectations. The injection was later repeated and subjected to further loading with the same results.

It appears that, when injected under pressure, the liquid silicone spreads under the slab and when it expands, fills all the voids. The cured foam then compresses and relaxes as the slab undergoes vertical excursions from either traffic loads or slab curl due to temperature change, thereby preventing the creation of any subsequent build up of eroded fines under the approach slab. This also prevents water from pumping in and out of the shoulder under traffic.

A subsequent field trial of the silicone material involving about 25 slabs was made to determine field applicability and equipment needs. When that was successful, a two mile project was planned and injected. Two additional projects, each about two miles in length, have also been treated, and another is nearing construction stage. These experiments indicate that only two injection ports per slab are necessary. The amount of liquid per slab varies, but is approximately one gallon per slab. The performance of these projects will be evaluated and reported at a later date.

At present, the cost of this treatment is rather high, with material cost running around $45 to $55 per gallon. It is hoped that increased (volume) usage and competition will bring the cost down. Also, it is understood that a closed cell polyurethane is now available. Provided that the setting time and expansion properties can be controlled as required and the other properties are satisfactory, this product could be a much cheaper solution to the problem.

PROGRESSION OF FAULTING

In 1968, a program was initiated to study the progression of faulting in various regions of the state. On selected sections, faulting was measured at 25 consecutive joints and averaged to obtain a faulting value for the project. Although the amount of displacement varied considerably from one joint to the next, the 25 joints were found from several experiments with up to 50 consecutive readings to be representative of the entire project. By periodically re-measuring the same joints, trends in rates of faulting could be determined. Generally, measurements were made 2 or 3 times per year.

The sections selected covered all climate regions of the state and included desert, coastal, valley and mountain areas. Pavement ages ranged from new to 13 years at time of initial measurement. Transverse joint spacing varied from a uniform 15 feet to a staggered spacing of 13, 12, 18, 19 feet (and repeat), with an experimental spacing of 8, 5, 7, 11 feet (and repeat). As experimental features were constructed, additional test sections were established.

Figures 1 through 24 show plots of the faulting data for some of the sections being monitored. Individual measurements show variability, but over a period of a few years faulting trends become evident. These plots were included in a previous report(4) but have been updated. Faulting is shown to begin almost immediately after a pavement is opened to traffic (regardless of region) and increases with time, although the rates of increase vary considerably. Those projects with the slowest rates are generally in the semiarid regions of the state (Figures 1, 2, 7, 8, 11, 19). Those with the greater rates are often in the mountain and coastal reigons where more rainfall or equivalent snowfall occur (Figures 10, 12, 16, 20, 22). The remainder of the projects are considered to be in the valley region and have faulting rates that are generally in between the two extremes.

Figures 13 through 16 show faulting of some experimental base and shoulder construction. The "control" listed in the figures refers to the standard pavement of 8 to 9 inch thickness and shoulders of aggregate base covered by 3 to 4 inches of asphalt concrete. None of the shoulder or base experimental treatments shown in Figures 13, 14, and 15 had any significant effect on faulting. Only the section where both an erosion-resistant LCB and a wedge of asphalt concrete along the pavement-base interface were used resulted in a reduction of the faulting rate (Figure 16).

Figure 12 shows a plot of faulting of a pavement that was ground in 1979 to restore riding quality. The data show that faulting is still continuing, and at approximately the same rate as before grinding.

Figure 22 shows data from a project that was overlaid with AC before the average faulting reached as high a level as the one in Figure 12. However, a number of individual measurements were about 0.20 inch, and the public generally notices the roughness when faulting exceeds 0.15 inch.

The faulting of five experimental pavement sections is shown in Figures 17 and 18. The sections with concrete base are performing surprisingly well considering there was no treatment to prevent movement of shoulder fines. Those with joint spacings of about 1/2 the normal length also show low faulting values, although for a given length of pavement, the total faulting approximates that of the control section. Thus, by distributing this total amount of faulting among a greater number of transverse joints by decreasing the joint spacing, the development of noticeable faults is delayed.

Forming transverse joints by inserting plastic strips in the fresh concrete was expected to provide some benefits in the reduction of faulting by eliminating the reservoir left by sawing which can collect water and fines. However, Figures 19 through 23 do not indicate any significant advantage of inserts over sawed joints.

Figure 24 shows faulting of sections with experimental shoulders. On portions of the projects, the outer shoulder was constructed full width with either asphalt concrete or portland cement concrete and full depth of the pavement at the pavement edge. As shown in the plot, both experimental shoulders indicate reduced faulting.

A few of the sections show no increase or even a slight decrease in faulting over the past few years. This was entirely unexpected, but the readings have been checked for accuracy. They were also reasonably consistent each time measurements were made. It appears the fines generated from the shoulder material were depleted from the leave slab to the extent the approach slab fines were ejected without replacement.

On some projects that were originally included in this study, edge drains have been installed. These projects are now included in a separate study.

SUMMARY

The factors involved in the faulting process have been identified and mitigation measures developed. The sources of fine material that cause the faulting should be eliminated. A nonerodible base should be constructed as well as a barrier along the pavement-base interface at the shoulder. On new construction, this has been provided for by requiring a treated permeable base, a lean concrete base, or an asphalt concrete base, along with a drainage system which includes slotted pipe, treated permeable material, and filter fabric to protect the permeable material from untreated shoulder material.

On previously constructed projects, a drainage system is being added. In some cases, grout has been injected to fill the voids under the slab but this practice has been discontinued pending the results of an ongoing study of the effectiveness of the procedure. Experiments are underway to evaluate other materials for stabilizing the fines already under the slabs. If the fines are not stabilized, it is likely that they will be ejected into the shoulder and eventually plug the permeable material and the slotted pipe.

<u>REFERENCES</u>

1. California Pavement Faulting Study, a Transportation Laboratory report, M&R 635167-1, January 1970.

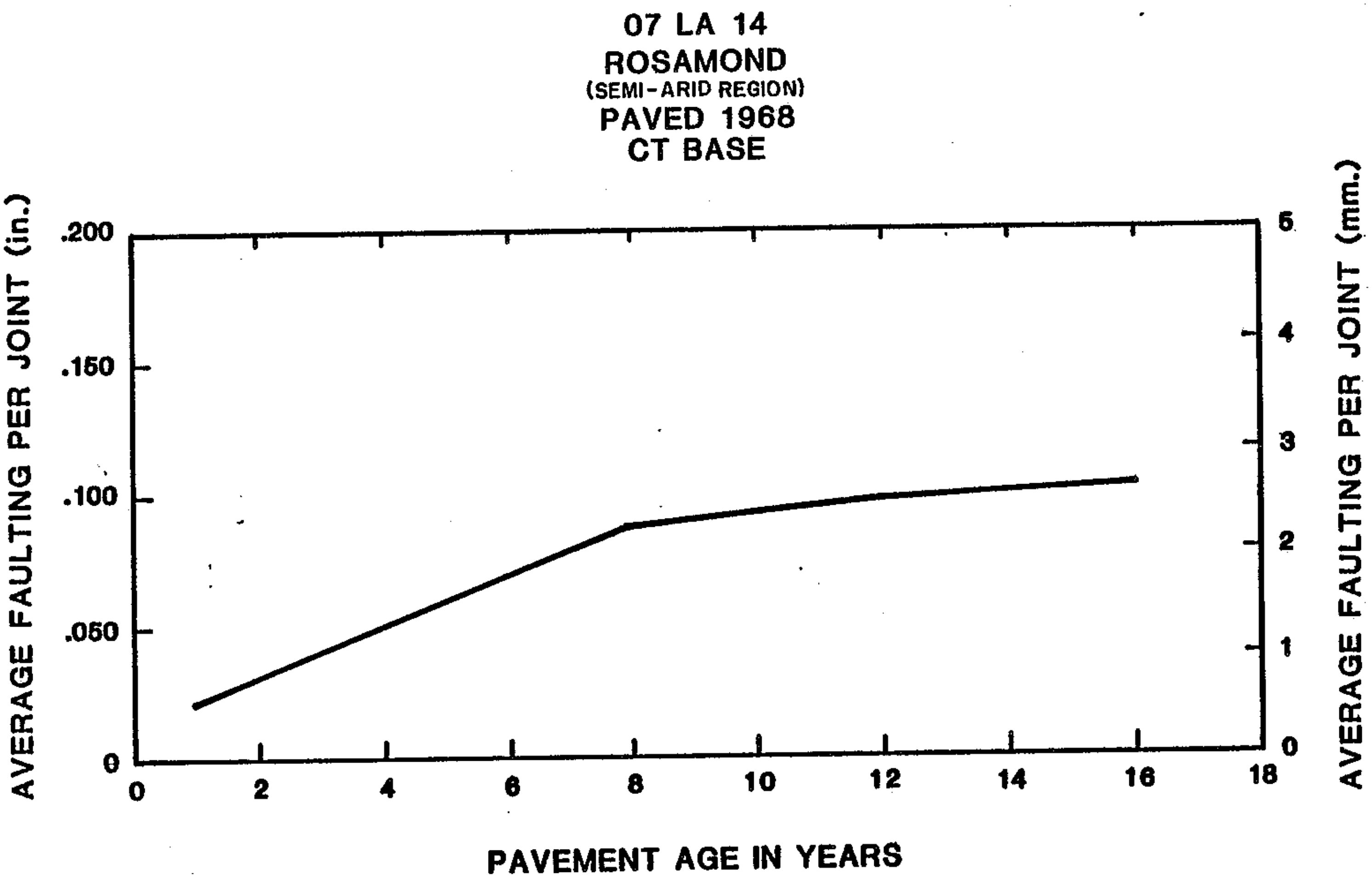
2. Faulting of Portland Cement Concrete Pavements, a Transportation Laboratory report, M&R 635167-2, January 1972.

3. Faulting of PCC Pavements, a Transportation Laboratory report, TL-5167-77-220, July 1977.

4. Model Slab Faulting Study, a Transportation Laboratory report, FHWA/CA/TL-80/23, June 1980.

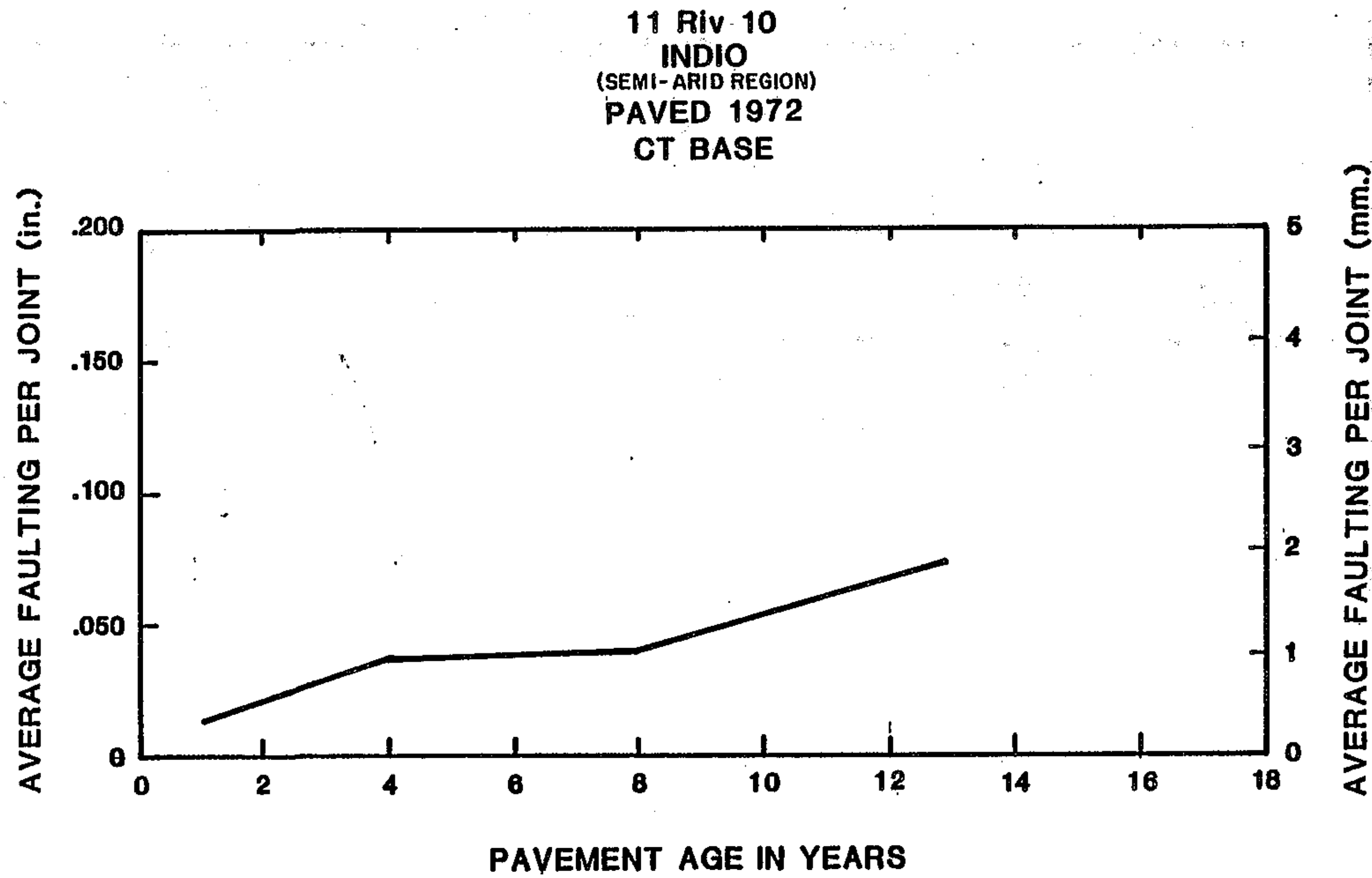
5. California Trials With Lean Concrete Base (LCB), a Transportation Laboratory report, TL-5167-3-75-37, October 1975.

6. Compare In-Situ Strength of Asphalt Concrete Base (ACB) to Cement Treated Base (CTB), a Transportation Laboratory report, TL-3110-1-74-17, December 1974.



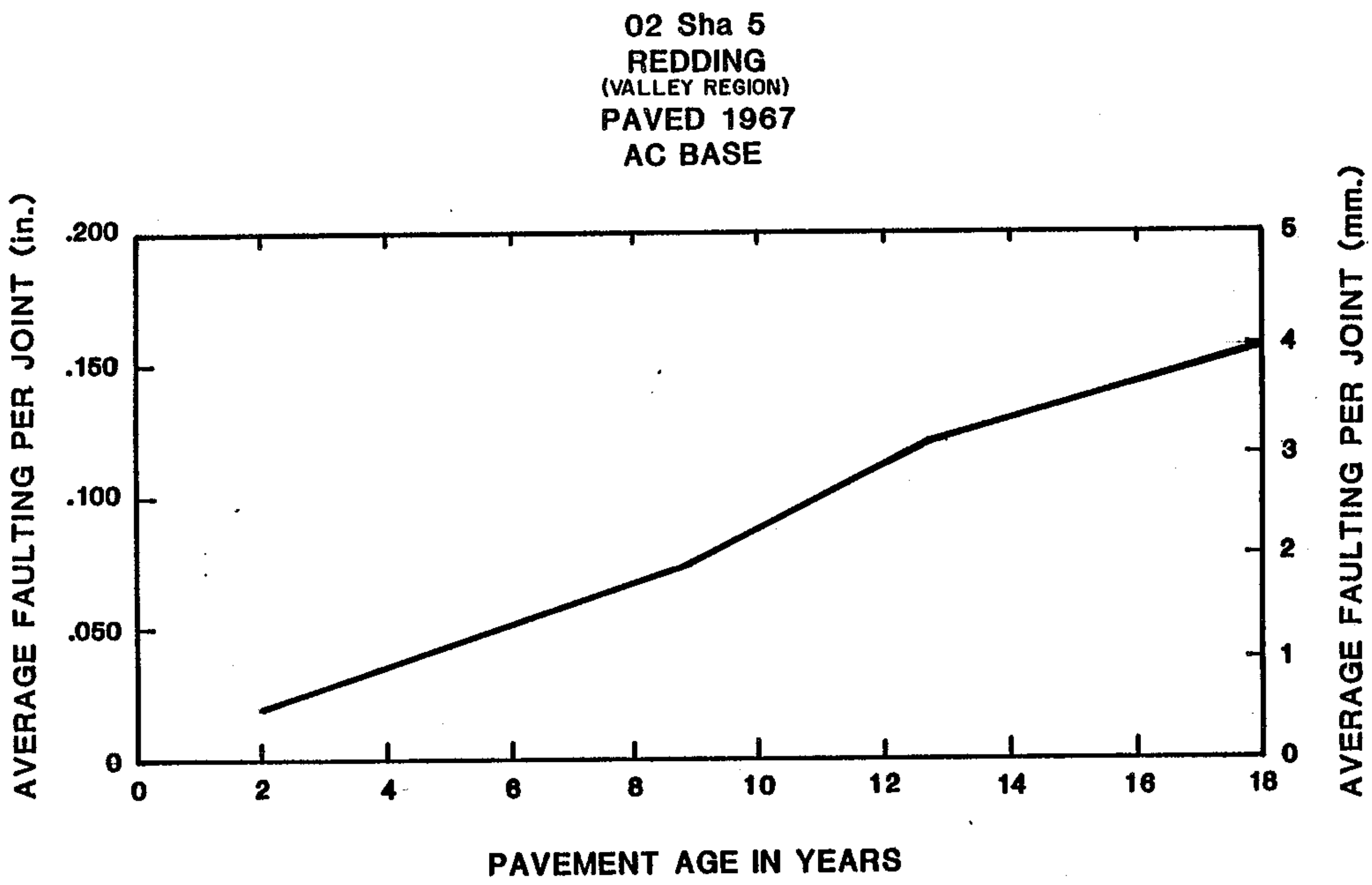
FAULTING TREND LINE

Figure 1



FAULTING TREND LINE

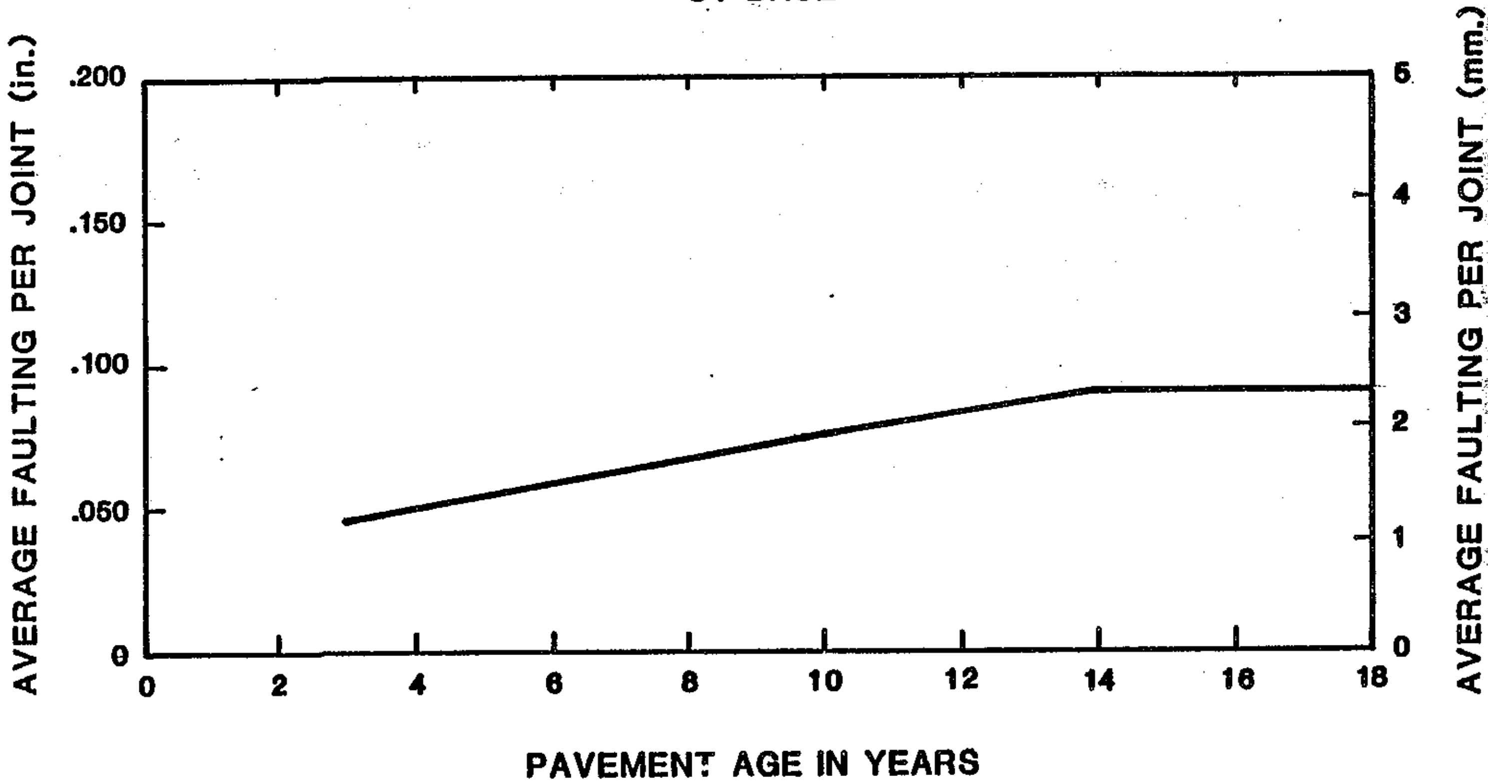
Figure 2



FAULTING TREND LINE

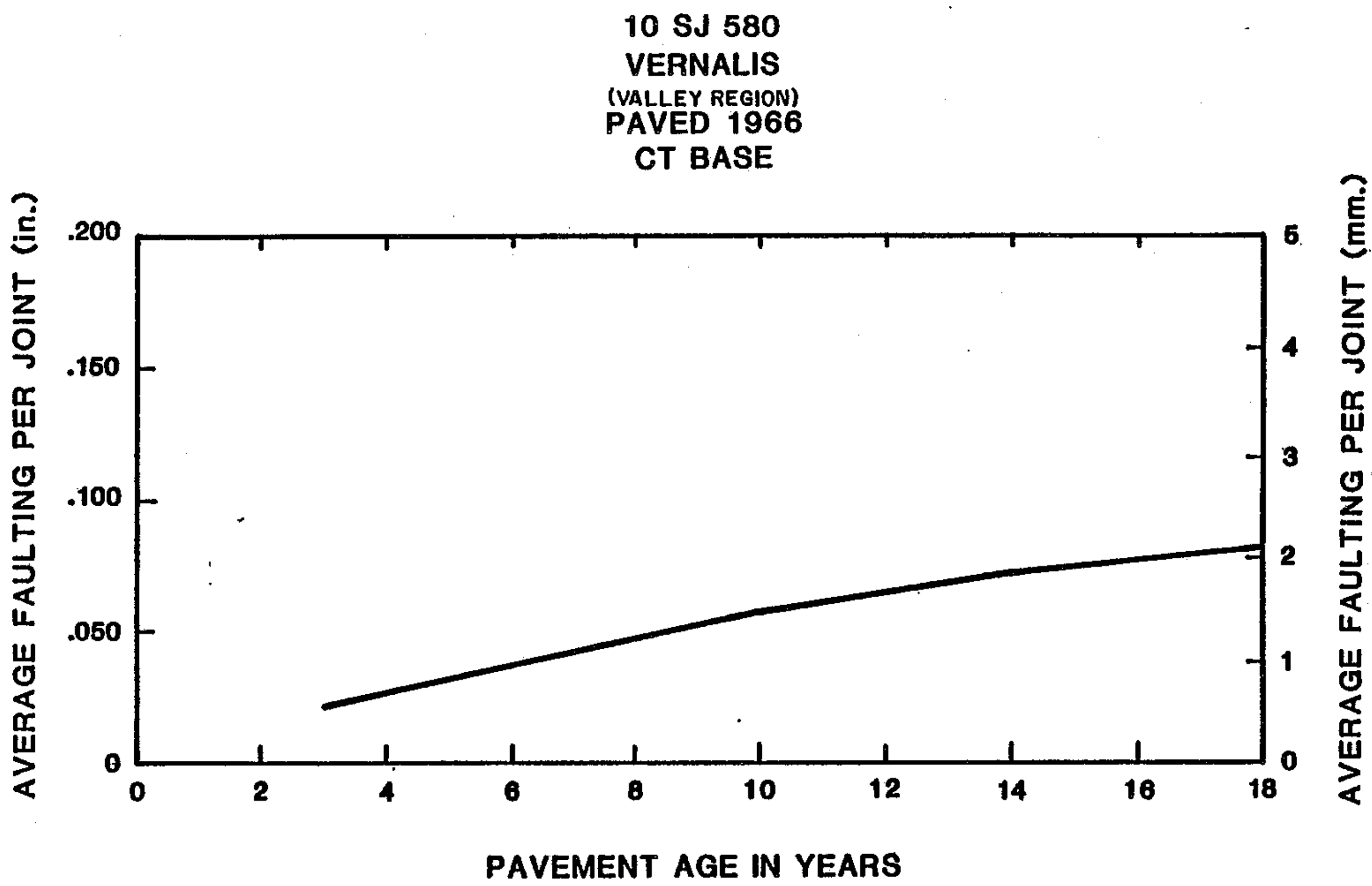
Figure 3

10 Mer 5
GUSTINE
(VALLEY REGION)
PAVED 1966
CT BASE



FAULTING TREND LINE

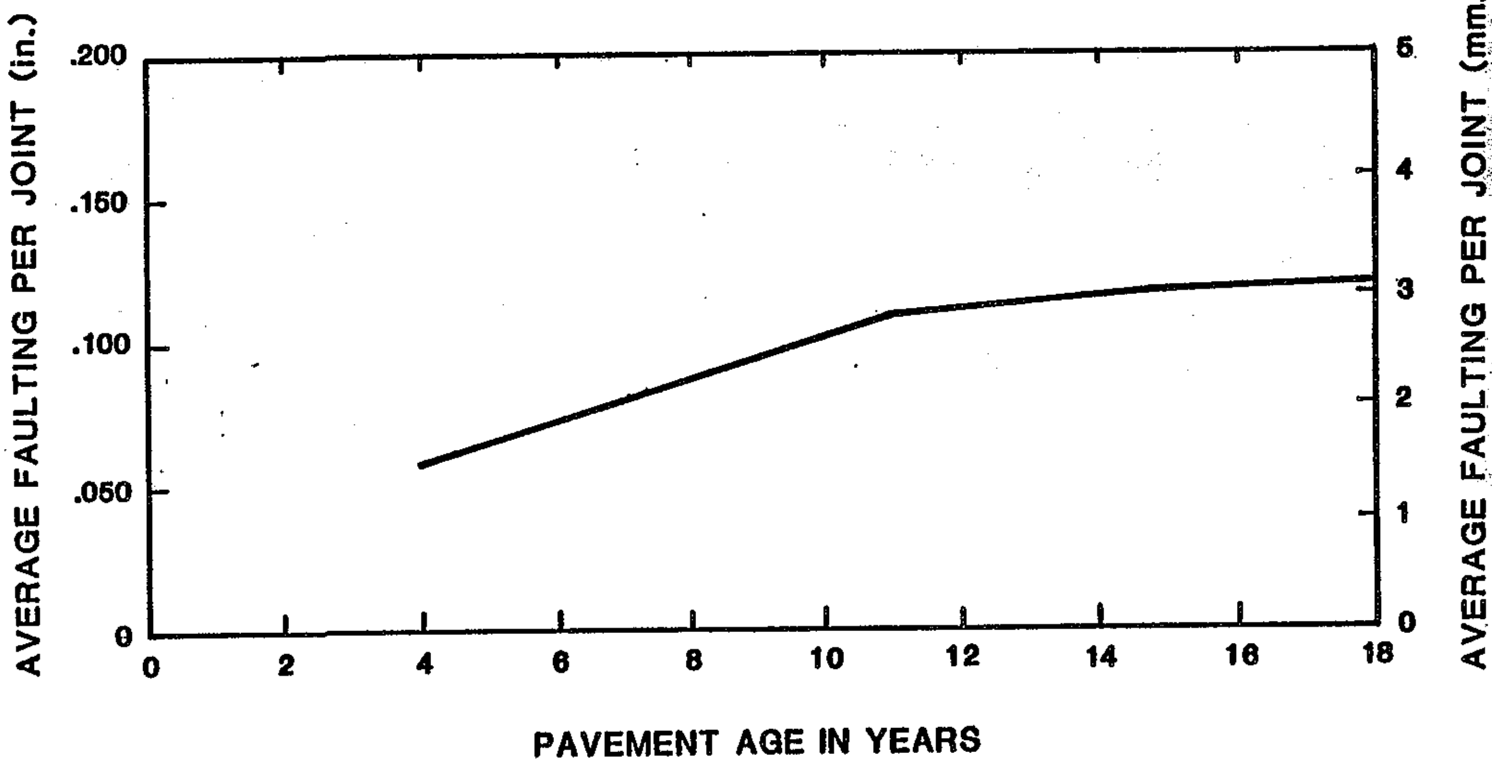
Figure 4



FAULTING TREND LINE

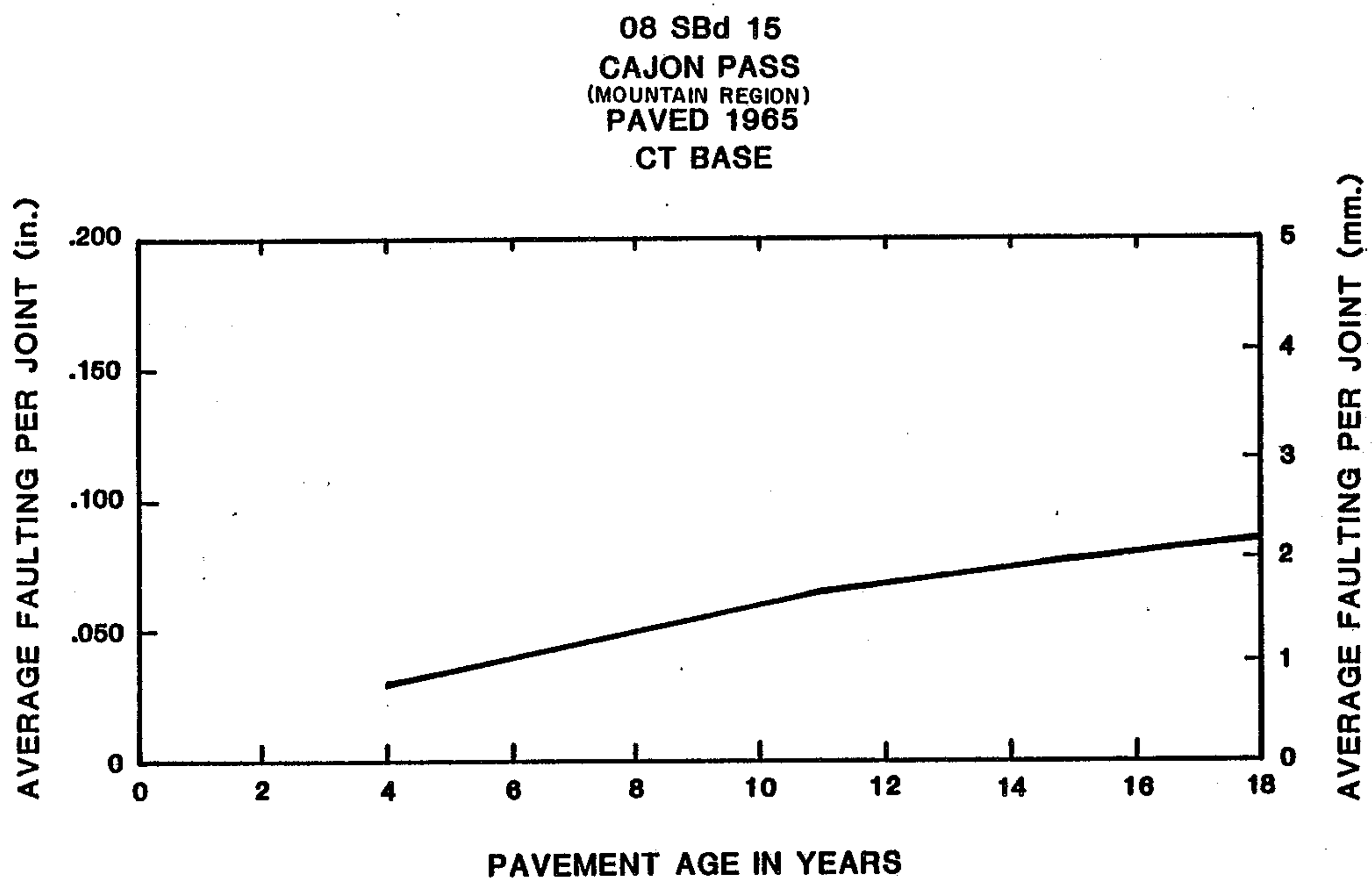
Figure 5

10 Mer 152
PACHECO PASS
(MOUNTAIN REGION)
PAVED 1965
CT BASE



FAULTING TREND LINE

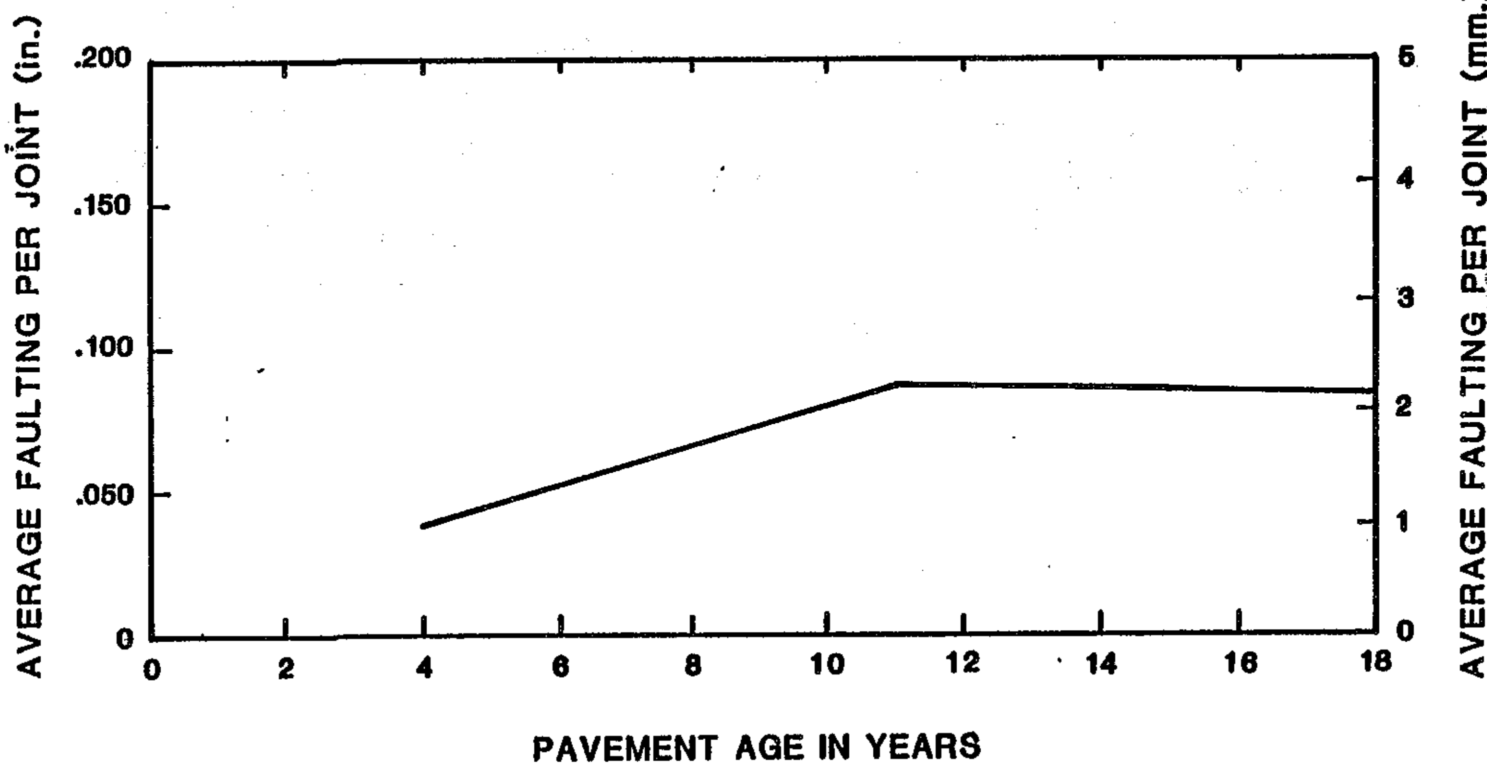
Figure 6



FAULTING TREND LINE

Figure 7

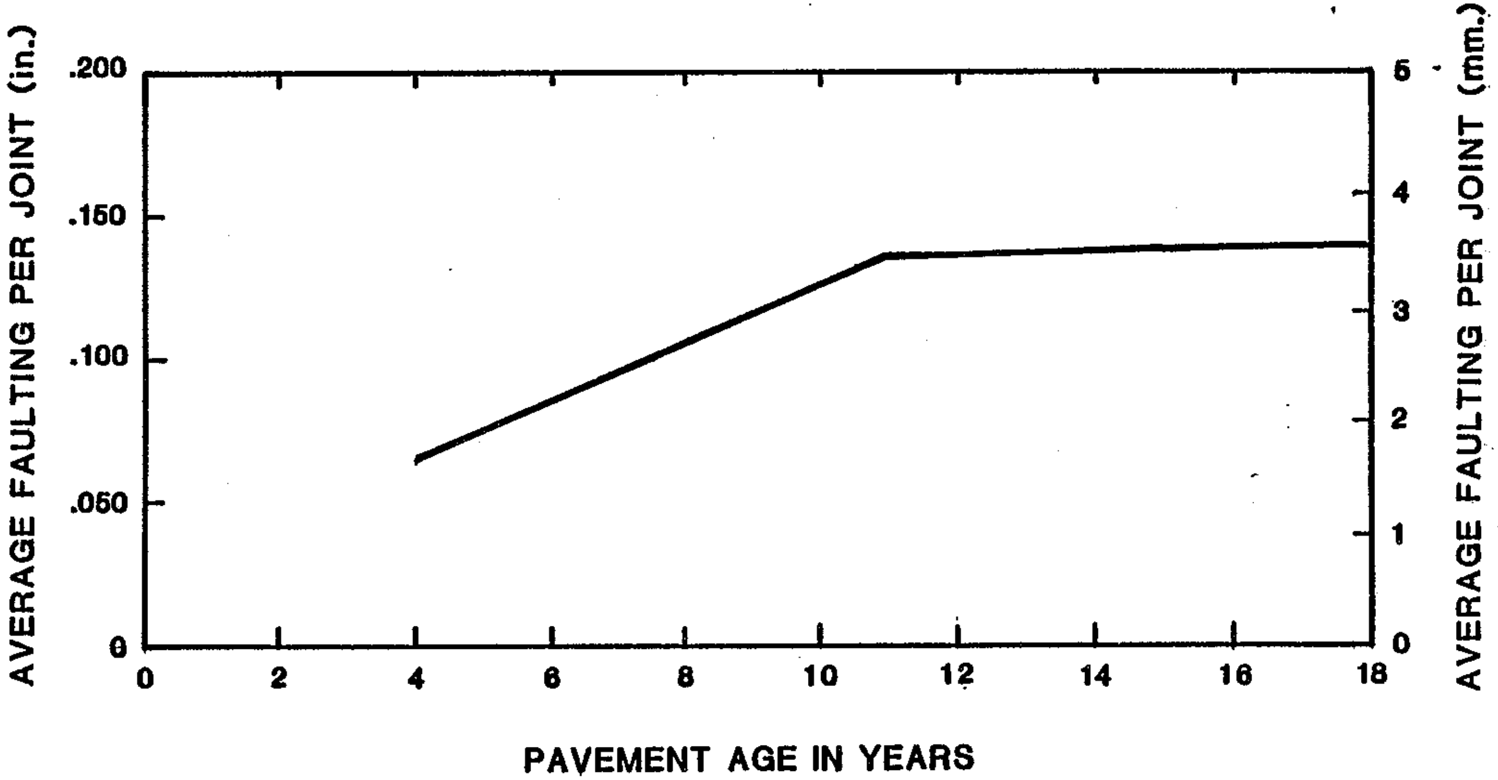
09 Kern 58
TEHACHAPI (WB)
(MOUNTAIN REGION)
PAVED 1965
AC BASE



FAULTING TREND LINE

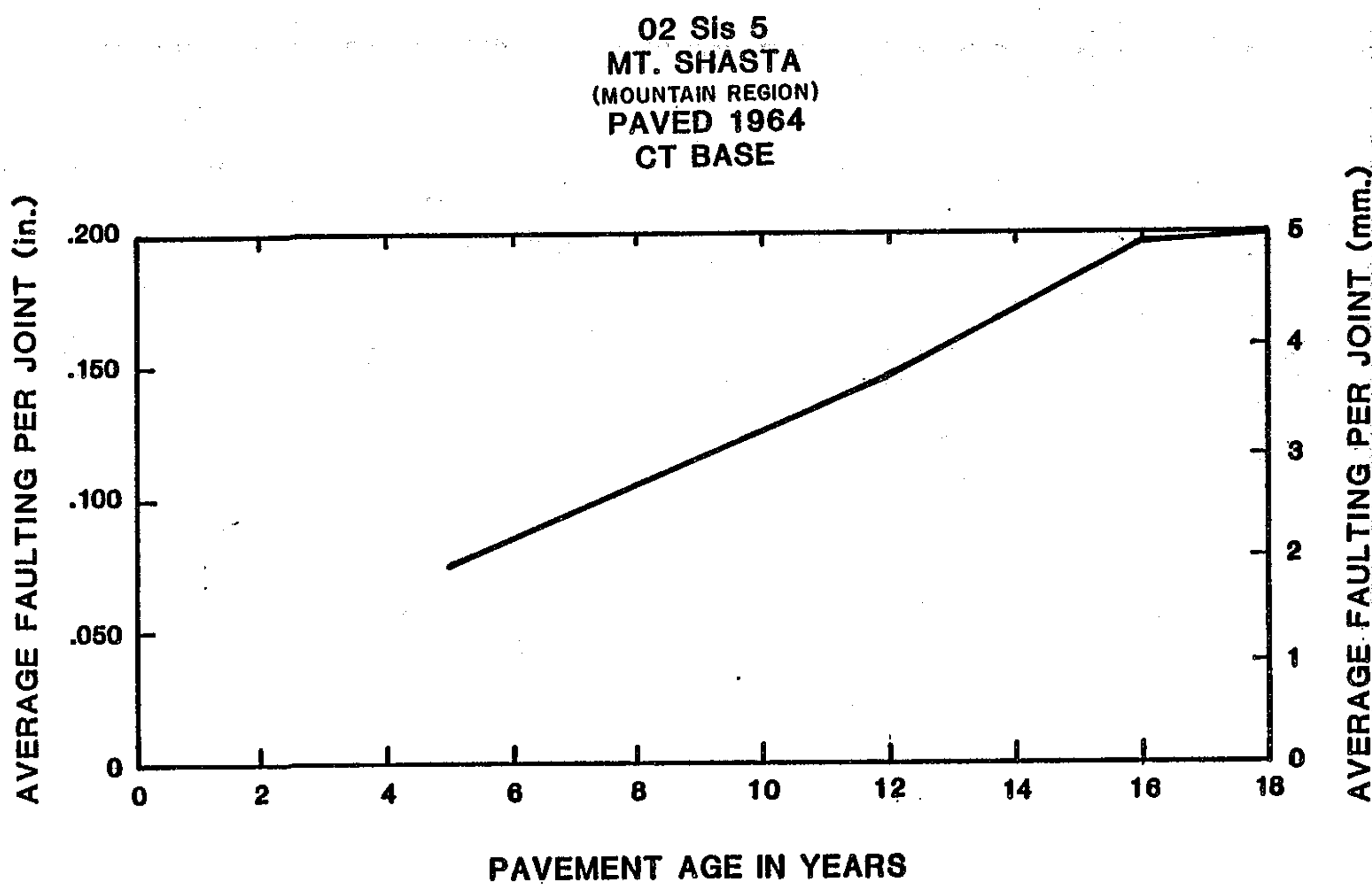
Figure 8

09 Ker 58
TEHACHAPI (EB)
(MOUNTAIN REGION)
PAVED 1965
CT BASE



FAULTING TREND LINE

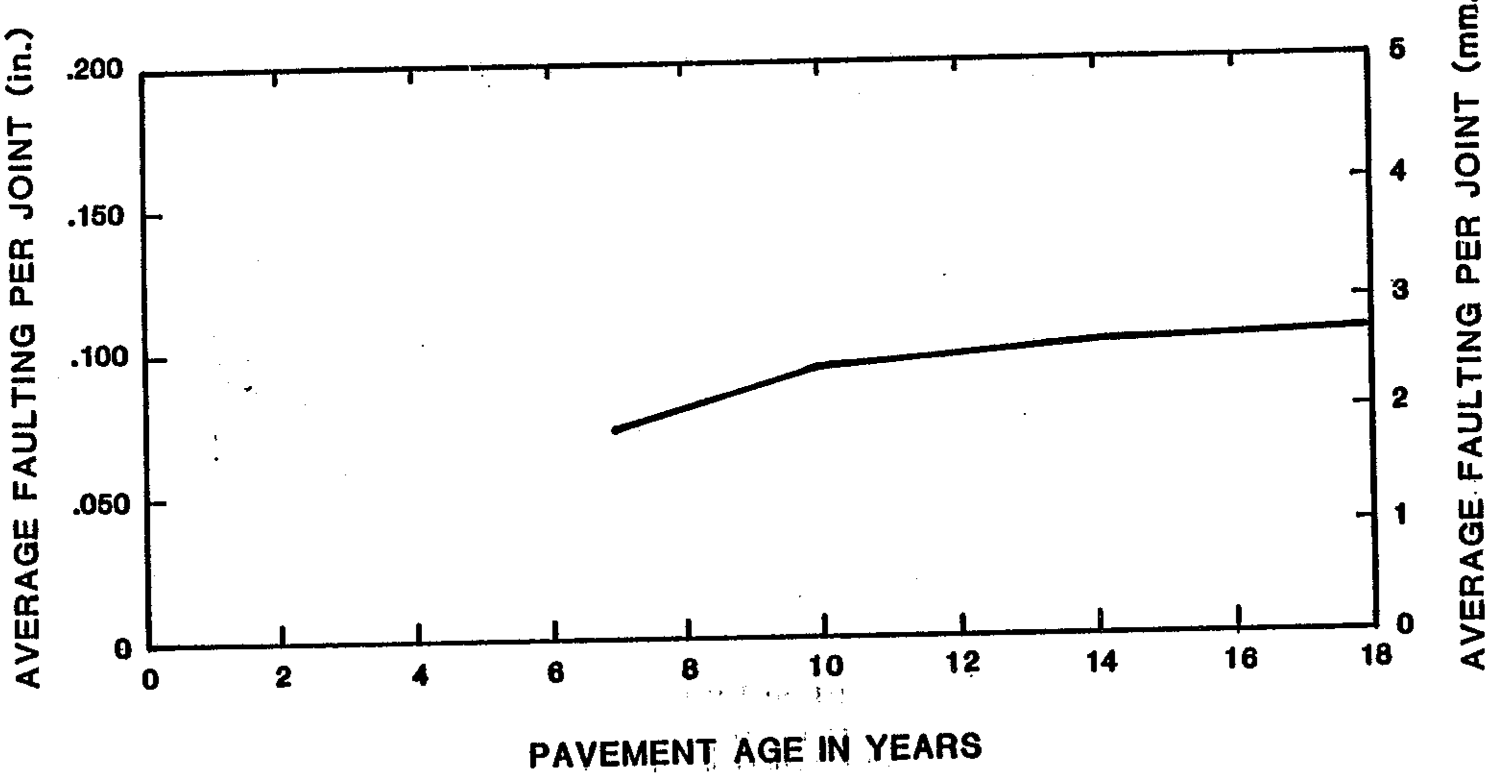
Figure 9



FAULTING TREND LINE

Figure 10

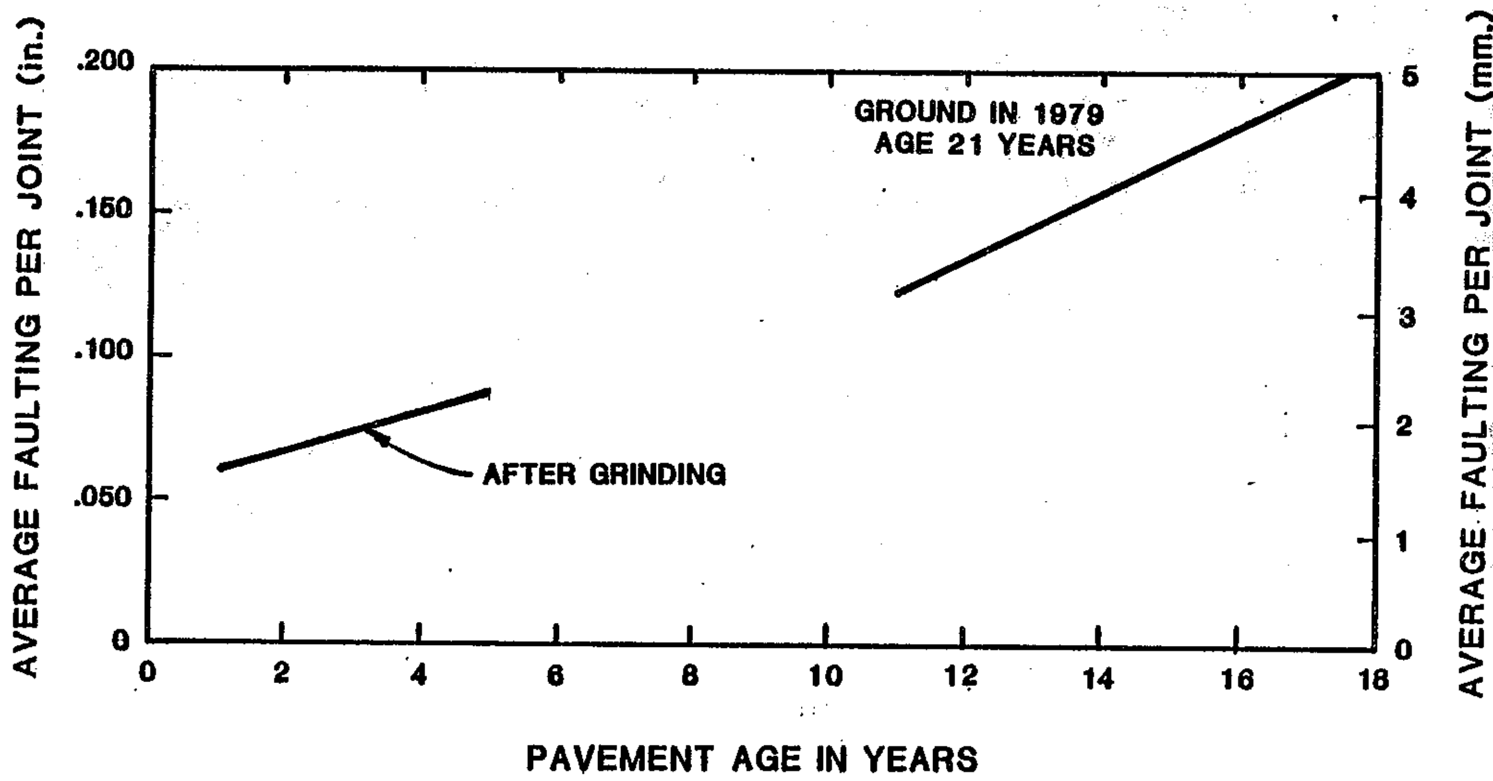
08 Riv 10
CABAZON
(SEMI-ARID REGION)
PAVED 1966
CT BASE



FAULTING TREND LINE

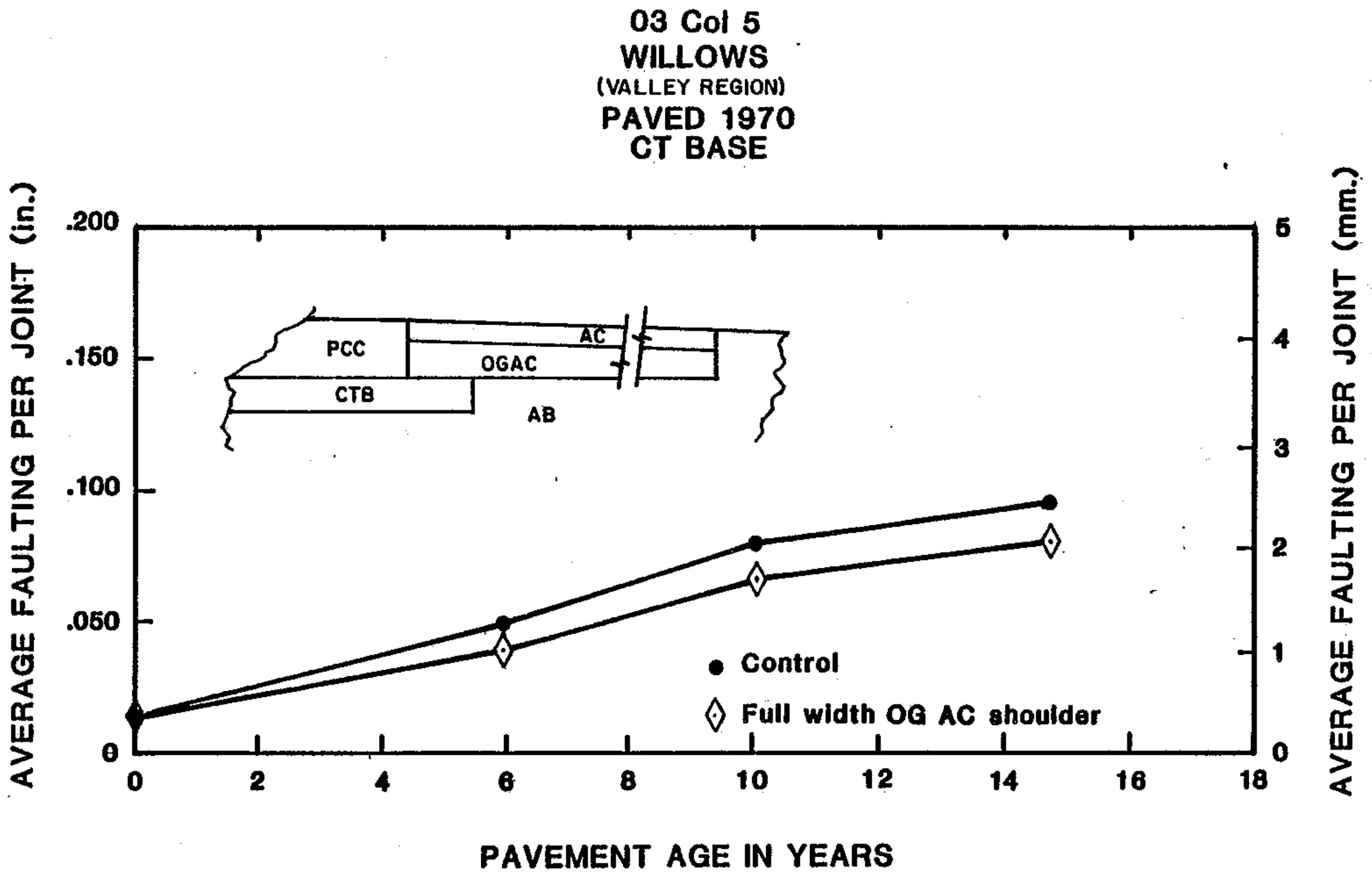
Figure 11

05 SB 101
ORELLA
(COASTAL REGION)
PAVED 1958
AT BASE



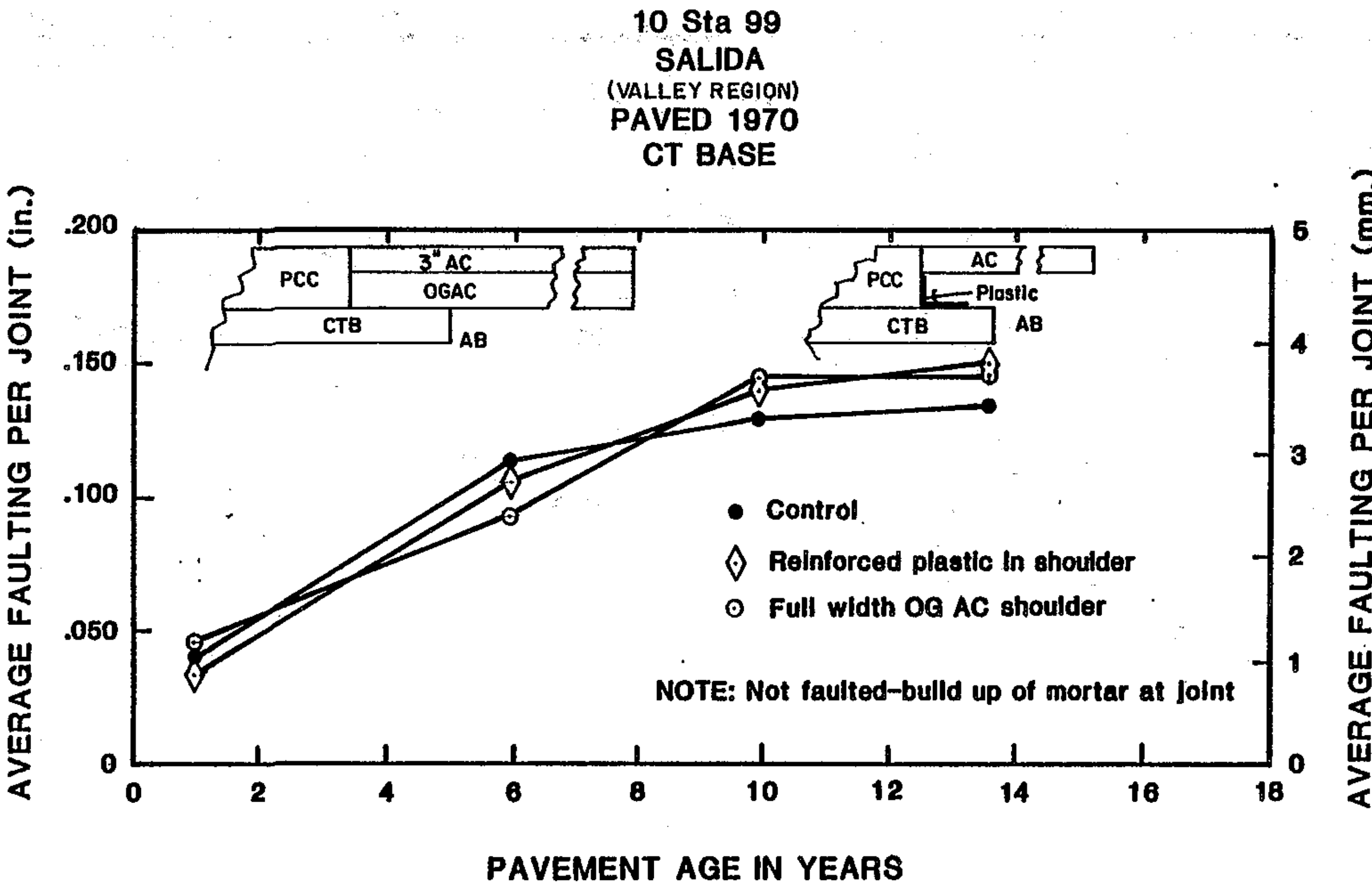
FAULTING TREND LINE

Figure 12



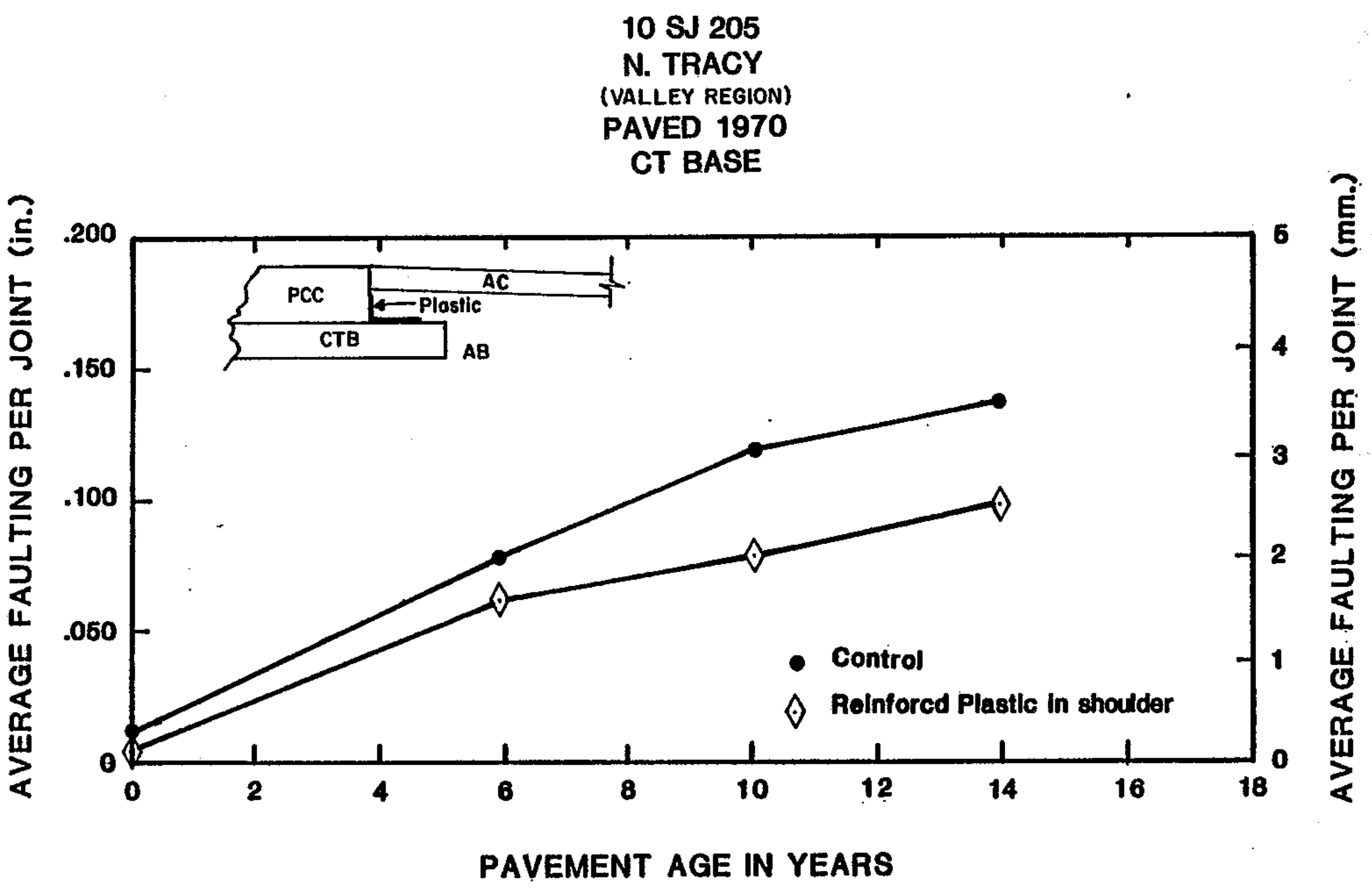
FAULTING TREND LINE

Figure 13



FAULTING TREND LINE

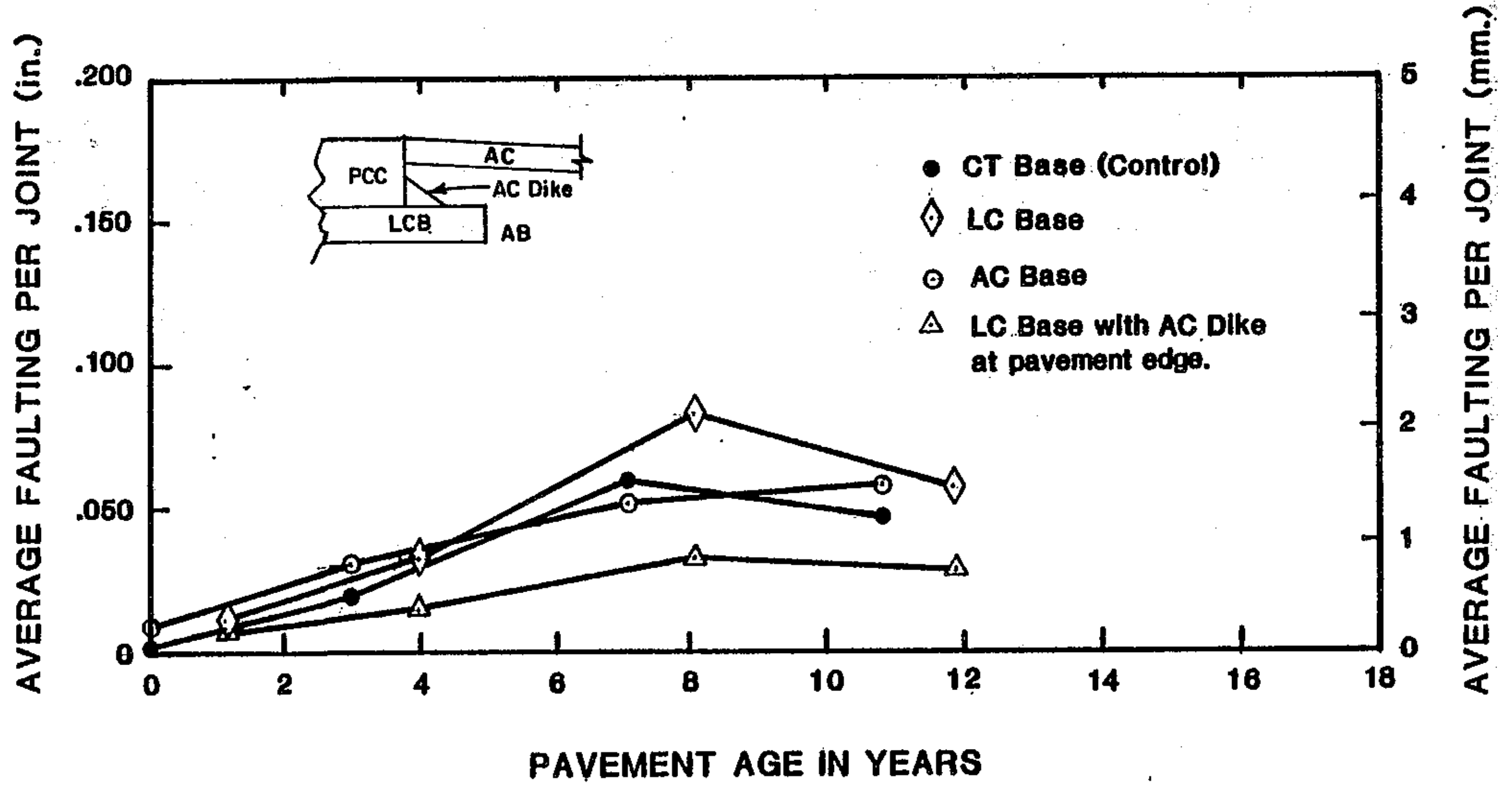
Figure 14



FAULTING TREND LINE

Figure 15

05 Mon 1
FORT ORD
(COASTAL REGION)
PAVED 1972 & 1973

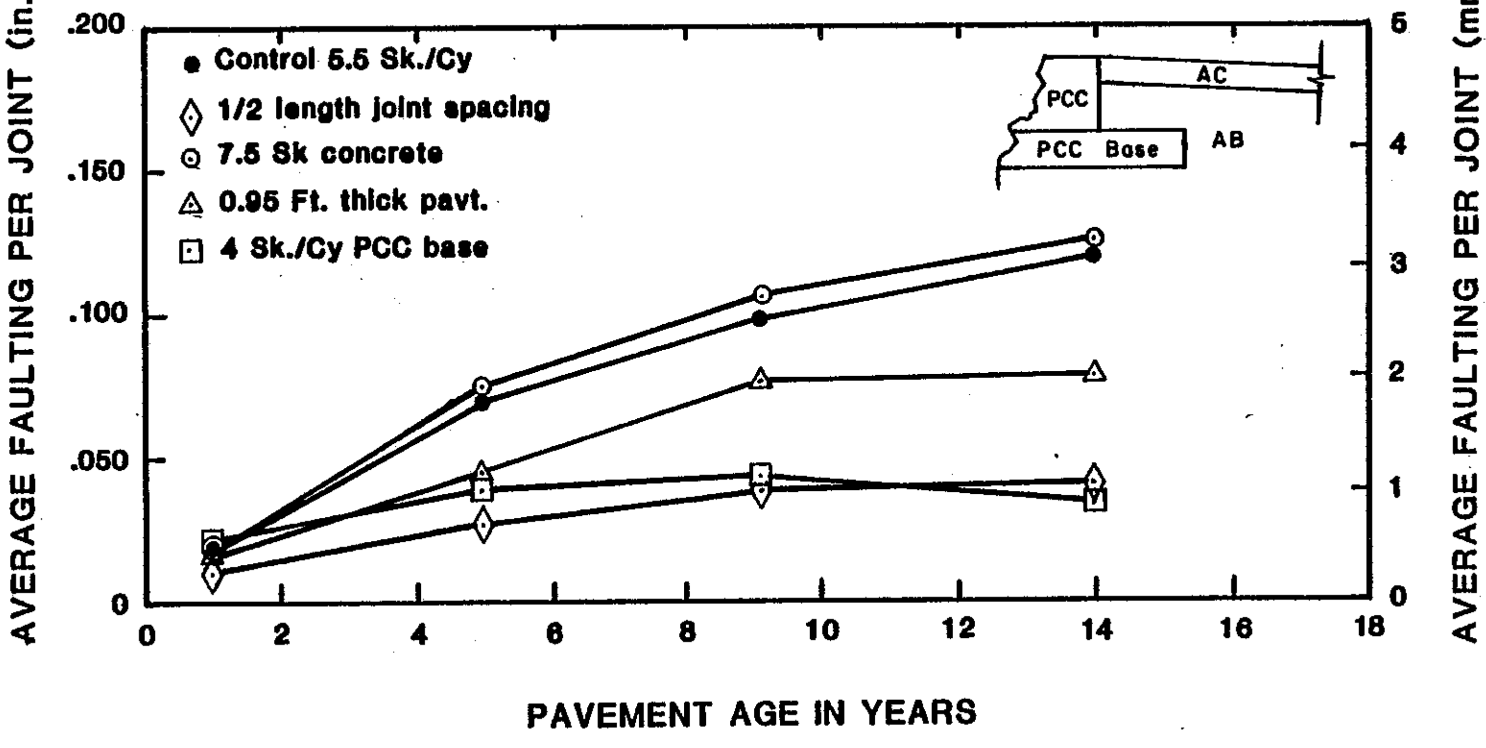


FAULTING TREND LINE

Figure 16

PAVEMENT JOINT FAULTING

10 SJ 5
E. TRACY (SB)
(VALLEY REGION)
PAVED 1971
CT BASE

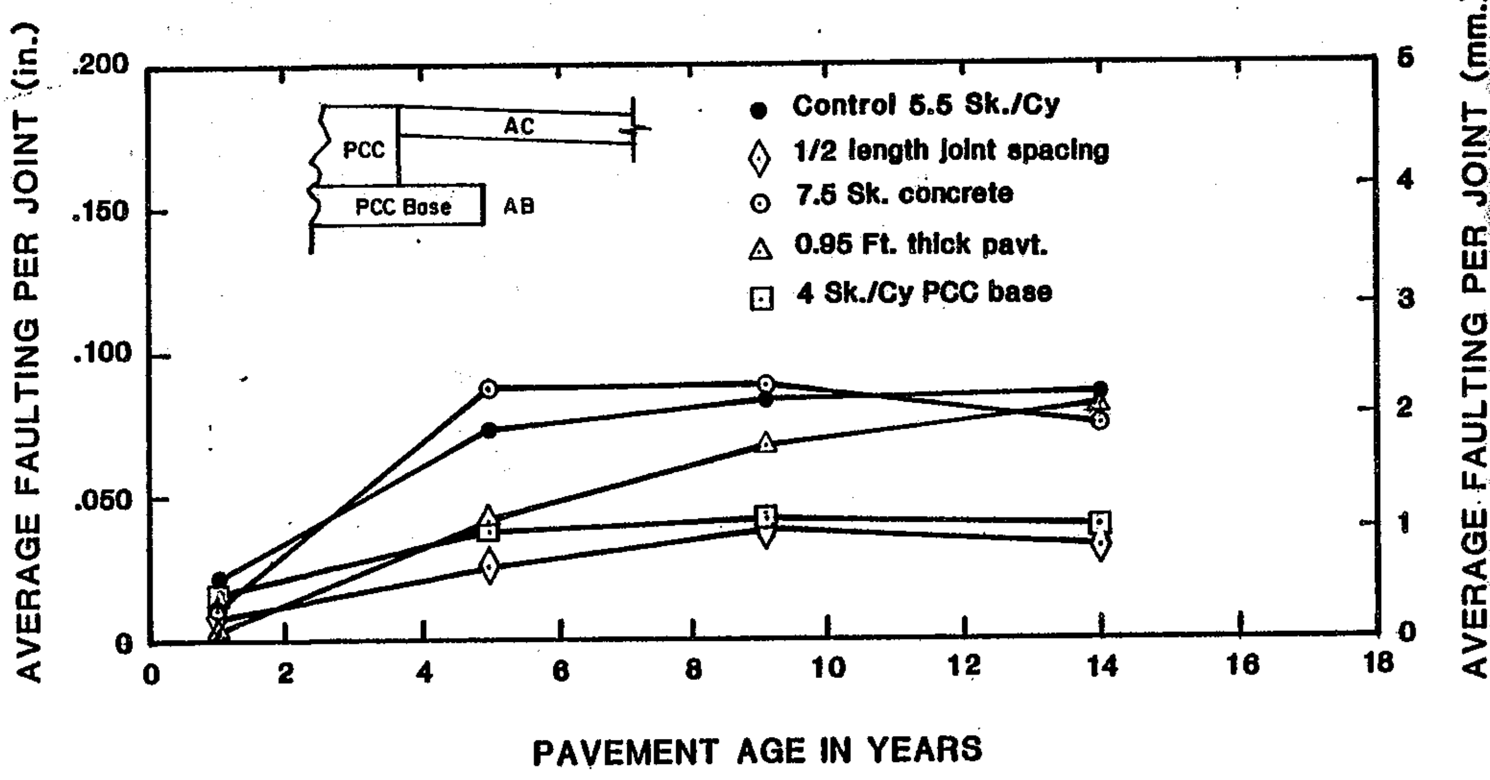


FAULTING TREND LINE

Figure 17

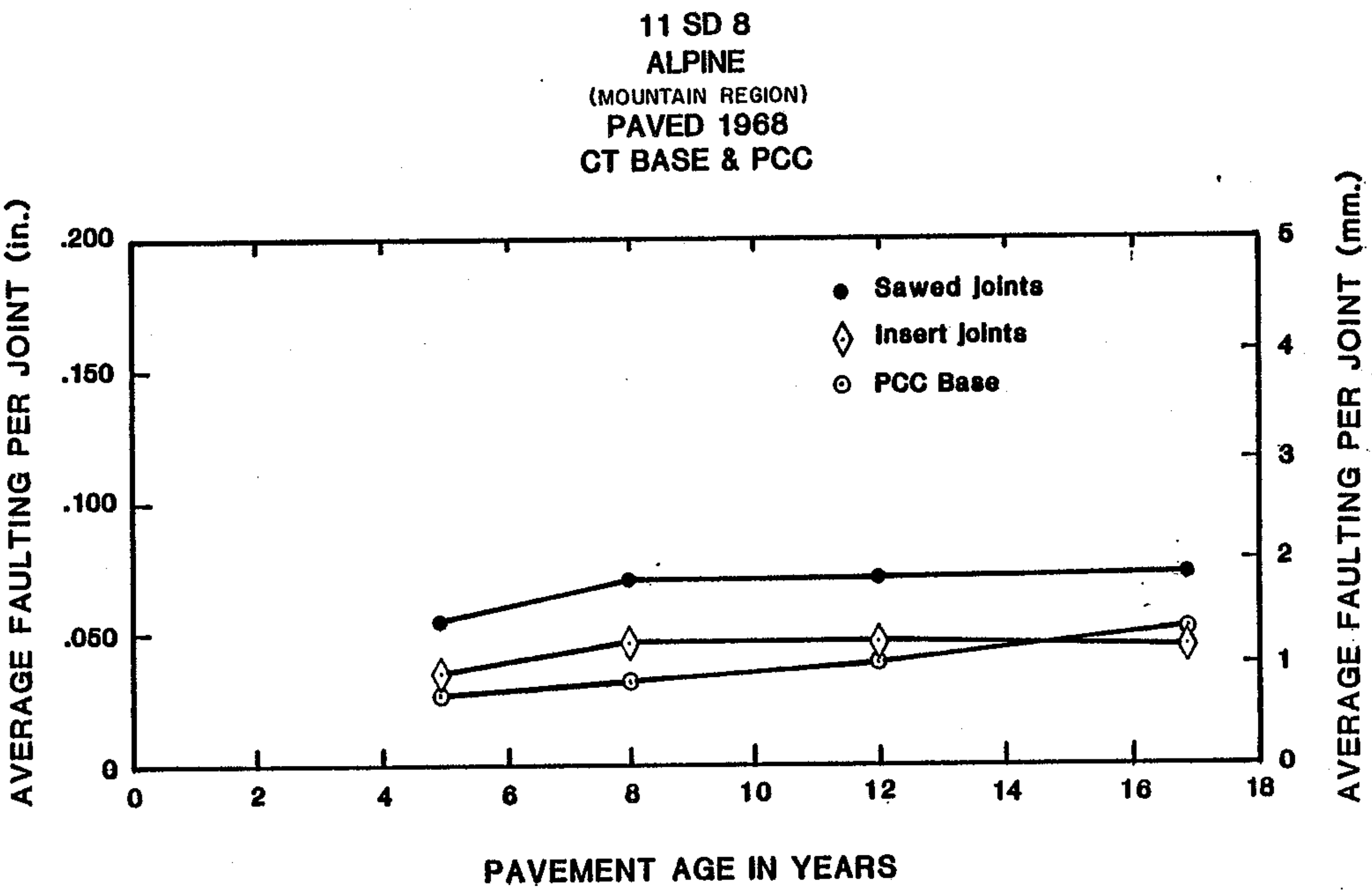
PAVEMENT JOINT FAULTING

10 SJ 5
E. TRACY (NB)
(VALLEY REGION)
PAVED 1971
CT BASE



FAULTING TREND LINE

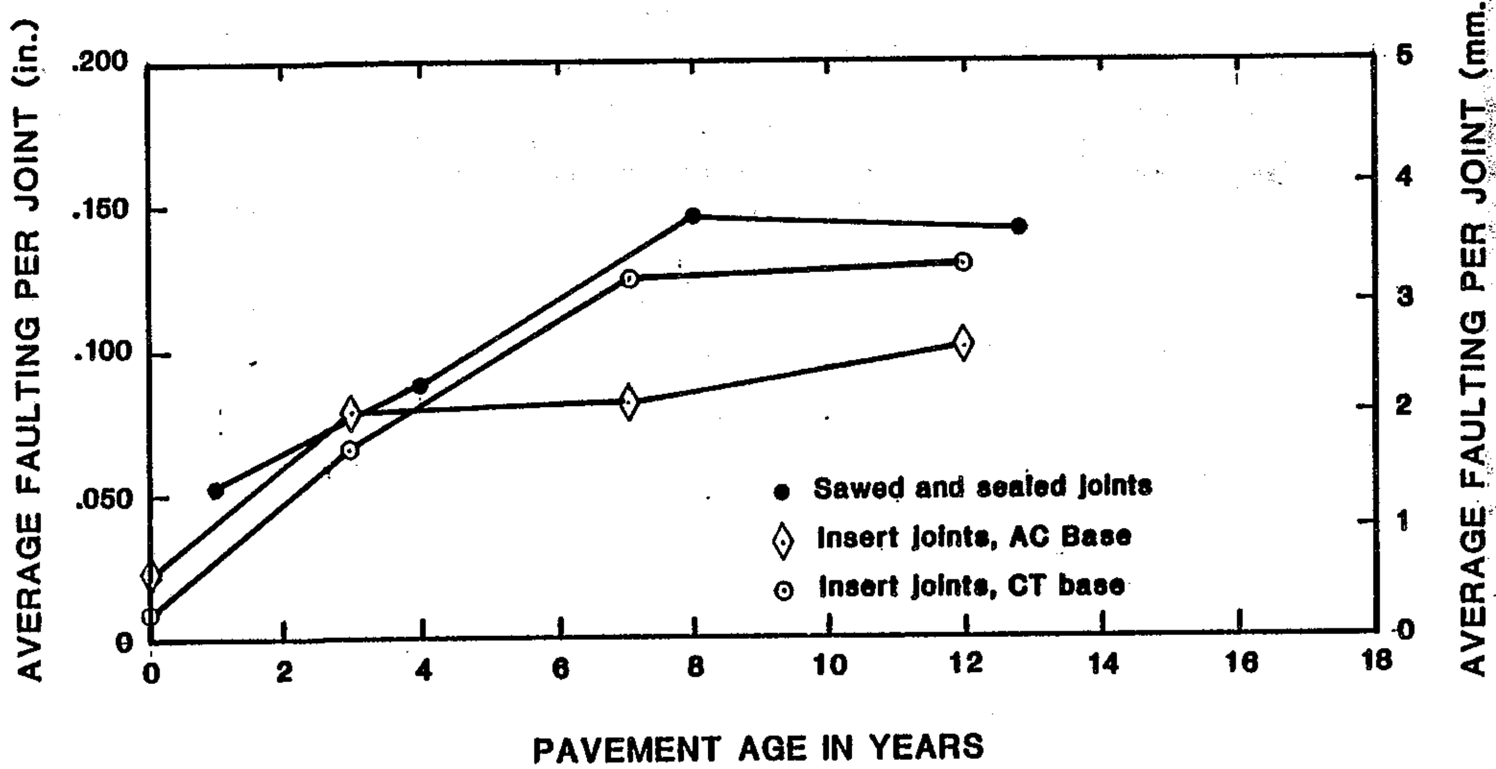
Figure 18



FAULTING TREND LINE

Figure 19

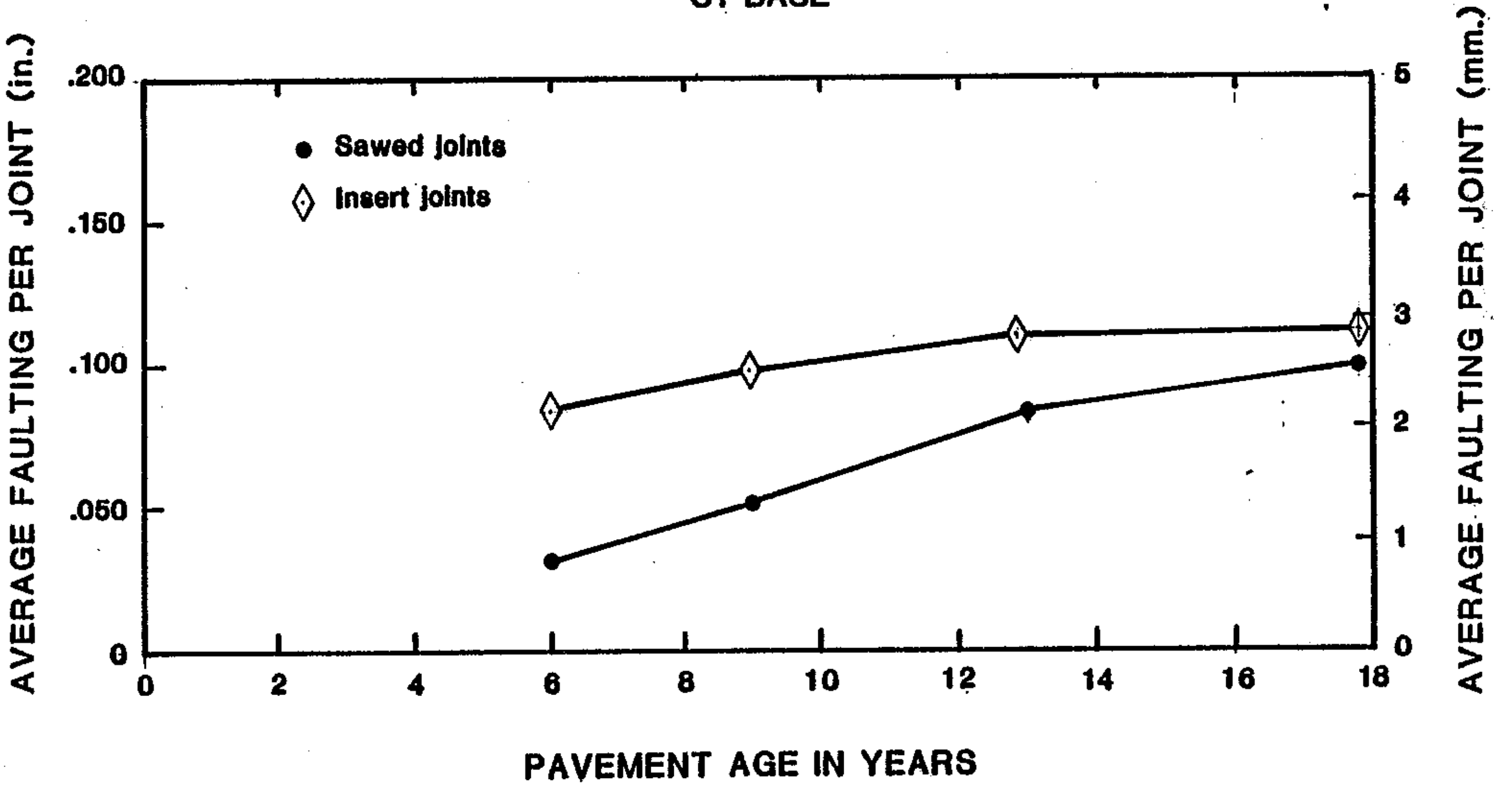
02 Sis 5
WEED
(MOUNTAIN REGION)
PAVED 1972 & 1973
CT & AC BASE



FAULTING TREND LINE

Figure 20

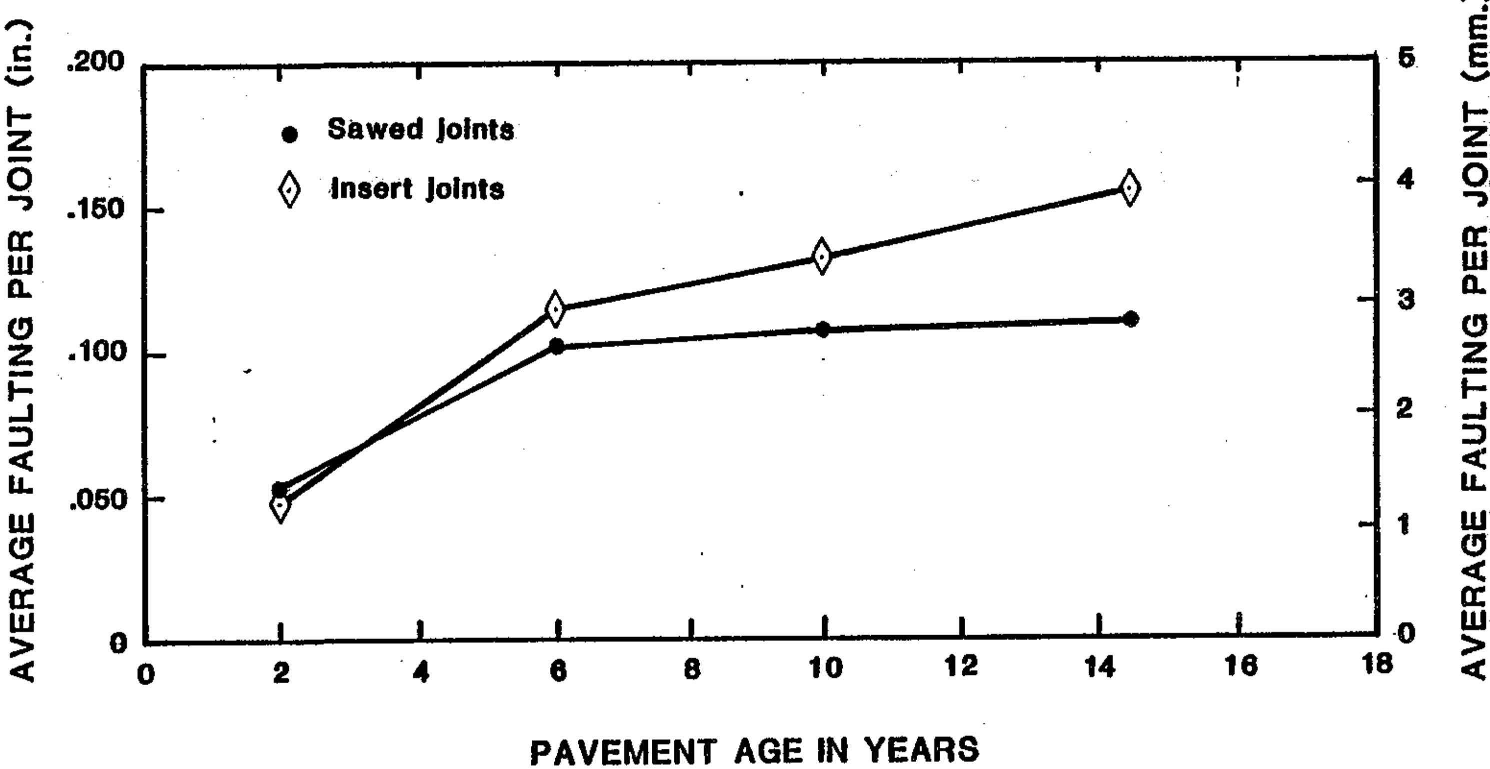
06 Mad 152
RED TOP
(MOUNTAIN REGION)
PAVED 1967
CT BASE



FAULTING TREND LINE

Figure 21

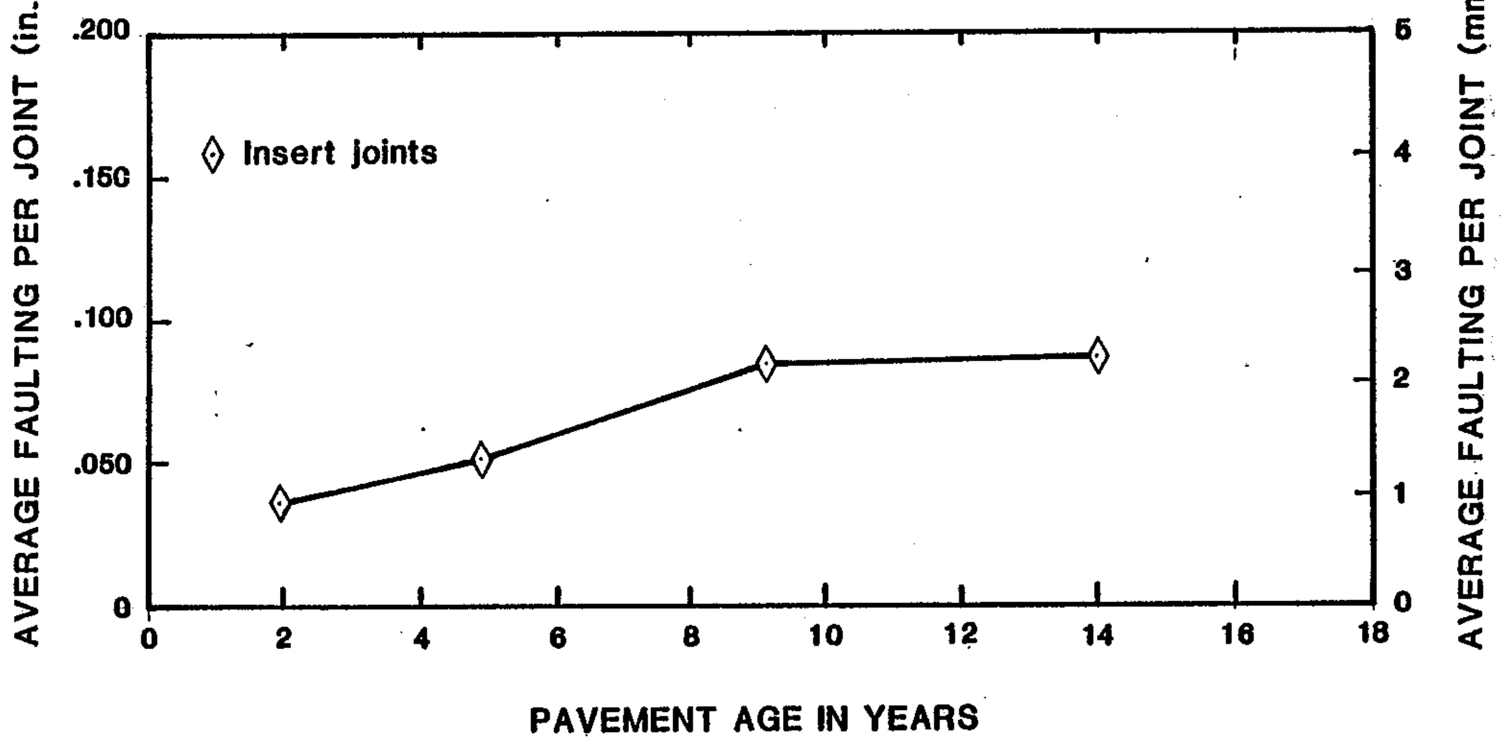
02 Sis 5
YREKA
(MOUNTAIN REGION)
PAVED 1970
CT BASE



FAULTING TREND LINE

Figure 22

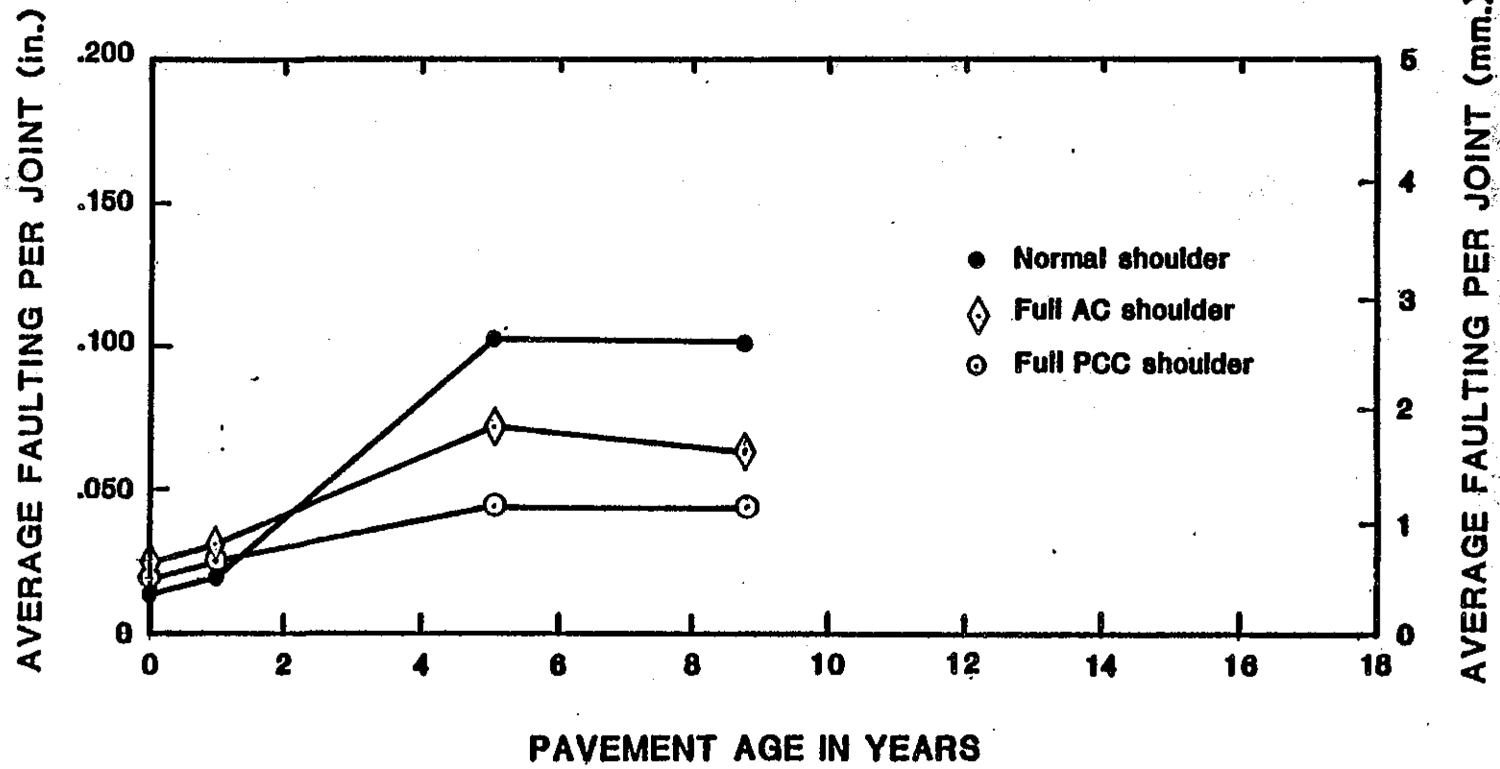
06 Tul 99
GOSHEN
(VALLEY REGION)
PAVED 1971
CT BASE



FAULTING TREND LINE

Figure 23

04 Son 101
GEYSERVILLE
(VALLEY REGION)
PAVED 1975
CT BASE



FAULTING TREND LINE

Figure 24

STATE OF CALIFORNIA
DEPARTMENT OF TRANSPORTATION
DIVISION OF CONSTRUCTION
OFFICE OF TRANSPORTATION LABORATORY

WATER-BASED CONCRETE CURING COMPOUNDS

Study Supervised by .... Earl C. Shirley, P.E.

Principal Investigator .... T. L. Shelly

Co-Investigator .... R. W. Ford

Report Prepared by .... R. W. Ford

G. L. RUSSELL, P.E.
Chief, Office of Transportation Laboratory

82-05

85-02

TECHNICAL REPORT STANDARD TITLE PAGE

1. REPORT NO.	2. GOVERNMENT ACCESSION NO.	3. RECIPIENT'S CATALOG NO.
FHWA/CA/TL-82/05		

4. TITLE AND SUBTITLE

Water-Based Concrete Curing Compounds

5. REPORT DATE

June 1982

6. PERFORMING ORGANIZATION CODE

7. AUTHOR(S)

R. W. Ford and T. L. Shelly

8. PERFORMING ORGANIZATION REPORT NO.

19704-604185

9. PERFORMING ORGANIZATION NAME AND ADDRESS

Office of Transportation Laboratory
California Department of Transportation
Sacramento, California 95819

10. WORK UNIT NO

11. CONTRACT OR GRANT NO.

E79TL16

12. SPONSORING AGENCY NAME AND ADDRESS

California Department of Transportation
Sacramento, California 95807

13. TYPE OF REPORT & PERIOD COVERED

Final
1979-82

14. SPONSORING AGENCY CODE

15. SUPPLEMENTARY NOTES

This study was conducted in cooperation with the U.S. Department of Transportation, Federal Highway Administration.

16. ABSTRACT

Proprietary water-based curing compounds were compared with solvent-based compounds now used by Caltrans. Water-based compounds protect concrete during the curing period as well as solvent-based compounds at a slightly lower cost.

A tentative specification for water-based curing compounds is included in this report.

17. KEY WORDS

Concrete curing compounds, water emulsions.

19. SECURITY CLASSIF. (OF THIS REPORT)	20. SECURITY CLASSIF. (OF THIS PAGE)	21. NO. OF PAGES	22. PRICE
Unclassified	Unclassified	30	

DS-TL-1242 (Rev.6/76)

NOTICE

The contents of this report reflect the views of the Office of Transportation Laboratory which is responsible for the facts and the accuracy of the data presented herein. The contents do not necessarily reflect the official views or policies of the State of California or the Federal Highway Administration. This report does not constitute a standard, specification, or regulation.

Neither the State of California nor the United States Government endorse products or manufacturers. Trade or manufacturers' names appear herein only because they are considered essential to the object of this document.

CONVERSION FACTORS

English to Metric System (SI) of Measurement

Quantity	English unit	Multiply by	To get metric equivalent
Length	inches (in)or(")	25.40 .02540	millimetres (mmm) metres (m)
	feet (ft)or(')	.3048	metres (m)
	miles (mi)	1.609	kilometres (km)
Area	square inches (in^2)	6.432×10^{-4}	square metres (m^2)
	square feet (ft^2) acres	.09290 .4047	square metres (m^2) hectares (ha)
Volume	gallons (gal)	3.785	litres (l)
	cubic feet (ft^3)	.02832	cubic metres (m^3)
	cubic yards (yd^3)	.7646	cubic metres (m^3)
Volume/Time (Flow)	cubic feet per second (ft^3/s)	28.317	litres per second (l/s)
	gallons per minute (gal/min)	.06309	litres per second (l/s)
Mass	pounds (lb)	.4536	kilograms (kg)
Velocity	miles per hour (mph) feet per second (fps)	.4470 .3048	metres per second (m/s) metres per second (m/s)
Acceleration	feet per second squared (ft/s^2)	.3048	metres per second squared (m/s^2)
	acceleration due to force of gravity (G)	9.807	metres per second squared (m/s^2)
Weight Density	pounds per cubic (lb/ft^3)	16.02	kilograms per cubic metre (kg/m^3)
Force	pounds (lbs) kips (1000 lbs)	4.448 4448	newtons (N) newtons (N)
Thermal Energy	British thermal unit (BTU)	1055	joules (J)
Mechanical Energy	foot-pounds (ft-lb) foot-kips (ft-k)	1.356 1356	joules (J) joules (J)
Bending Moment or Torque	inch-pounds (ft-lbs) foot-pounds (ft-lbs)	.1130 1.356	newton-metres (Nm) newton-metres (Nm)
Pressure	pounds per square inch (psi)	6895	pascals (Pa)
	pounds per square foot (psf)	47.88	pascals (Pa)
Stress Intensity	kips per square inch square root inch (ksi $\sqrt{in}$)	1.0988	mega pascals $\sqrt{metre}$ (MPa $\sqrt{m}$)
	pounds per square inch square root inch (psi $\sqrt{in}$)	1.0988	kilo pascals $\sqrt{metre}$ (KPa $\sqrt{m}$)
Plane Angle	degrees (°)	0.0175	radians (rad)
Temperature	degrees fahrenheit (F)	$\frac{tF - 32}{1.8} = tC$	degrees celsius (°C)

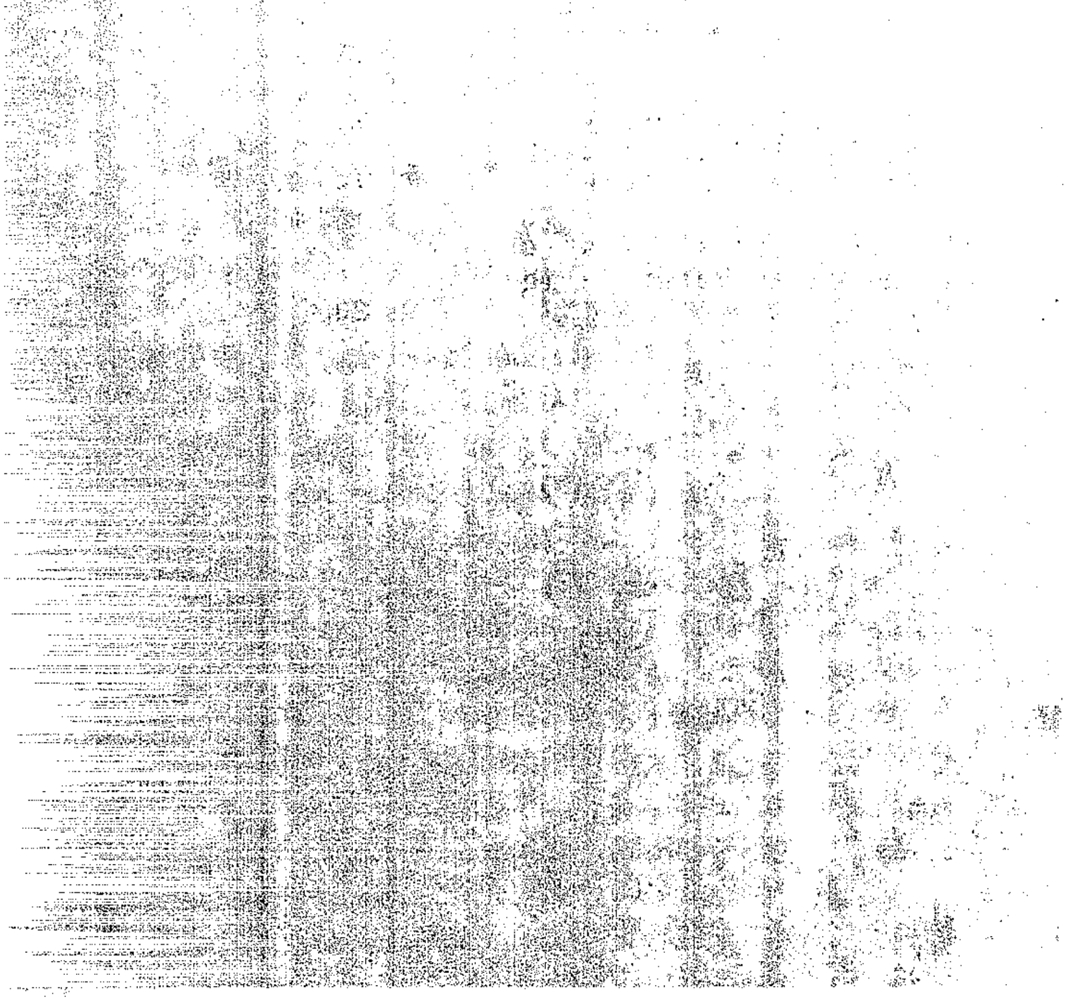
ACKNOWLEDGEMENTS

The authors wish to thank the many curing compound producers and raw materials suppliers who furnished samples and offered suggestions during the course of this project.

They also wish to thank members of the Transportation Laboratory staff from the Structural Materials, Soil Mechanics and Pavement, and Enviro-Chemical Branches who performed tests or assisted in obtaining materials needed for preparing test specimens.

TABLE OF CONTENTS

LIST OF TABLES



LIST OF FIGURES

INTRODUCTION

Freshly placed portland cement concrete is subject to damage when winds, low relative humidity and elevated temperatures cause excessive evaporation of moisture from the surface layer of the concrete. Such damage may be avoided or reduced by providing a continuing supply of moisture or by applying a vapor barrier to exposed surfaces. Moisture for curing may be supplied via ponding, wet mats or fogging. Vapor barriers may be applied either as solid films of paper, plastic film, etc., or as liquids which dry to form solid films, e.g., concrete curing compounds.

The materials now used by Caltrans as curing compounds are essentially varnishes or paints. The vehicle portion is a solution or suspension of wax, drying oil, or resin in a volatile organic solvent. In situations where fresh concrete requires protection from hot sun, pigments are suspended in the vehicle. When it is desirable to retain the natural appearance of the concrete, e.g., with exposed aggregate, a clear vehicle or vehicle containing a fugitive dye may be used as a curing compound.

Two recent developments will cause the abandonment of the solvent-based types of curing compounds now specified by Caltrans. First, the use of volatile organic solvents in coatings will be severely restricted by air pollution control regulations. The Model Rule for Architectural Coatings, approved July 7, 1977, by the California Air Resources Board (CARB), limits volatile organic solvents in architectural coatings to a maximum of 250 grams per

litre of coating (minus water) as applied. Concrete curing compounds are to be exempt from the ruling until September 2, 1982.

Since 1977 a number of CARB hearings have considered more or less restrictive regulations. Although the exact limits of the 1977 model rule may not be applied to concrete curing compounds, very similar regulations are expected to be enforced.

Secondly, volatile organic solvents may be expected to become increasingly costly and difficult to obtain as world petroleum resources become depleted. During a period of rising construction costs and tightening budgets, materials costs are very important. That is, the move to reduce volatile organic solvents content in compliance with air pollution control regulations will make economic sense.

This research project was initiated in 1979 to test curing compound formulations with low volatility and to develop specifications for their use by Caltrans. Formulations which would comply with the CARB guidelines could be 100% solids, high solids, or water-based materials. Both 100% solids and high solids coatings are expected to have higher material costs than either the solvent-based compounds now in use or water-based materials. Both 100% solids and high solids curing compounds would require costly modifications of application equipment and procedures. Water-based compounds are expected to be competitive with existing Caltrans specification curing compounds, and they can be applied using the equipment and procedures now in use on Caltrans projects.

Our 1979 literature survey indicated that, except for linseed-oil-based formulations, little work had been done to develop curing compounds with low volatile organic solvent contents. By writing to a number of curing compound manufacturers and paint raw materials suppliers, we obtained 23 samples of curing compounds for evaluation. Preliminary screening tests for conformance to CARB guidelines for low volatile organic solvent content and water retention test eliminated approximately two-thirds of the formulations submitted. Density, viscosity, drying time and freeze-thaw resistance tests were also performed to establish parameters for identification and quality control. Four satisfactory formulations, representative of the water-based types submitted for evaluation, were compared to solvent-based compounds for their influence on compressive strength, flexural strength and abrasion resistance of 3"x3"x11" concrete beams cured under laboratory conditions (73$\pm$3°F, 50% relative humidity). They proved to be approximately equivalent in effect. A repetition of strength and abrasion resistance tests, performed using a 4'x6'x0.75' concrete slab under field conditions (70-90°F), demonstrated again the approximate equivalence of the water-based curing compounds to solvent-based curing compounds.

Using materials costs furnished by a curing compound manufacturer, we determined that, at the rates of application specified, the water-based curing compounds cost somewhat less to use than solvent-based compounds. A tentative performance type specification for water-based concrete curing compounds was written for use on Caltrans projects.

CONCLUSIONS

1. Water-based curing compounds can be used in lieu of solvent-based systems.

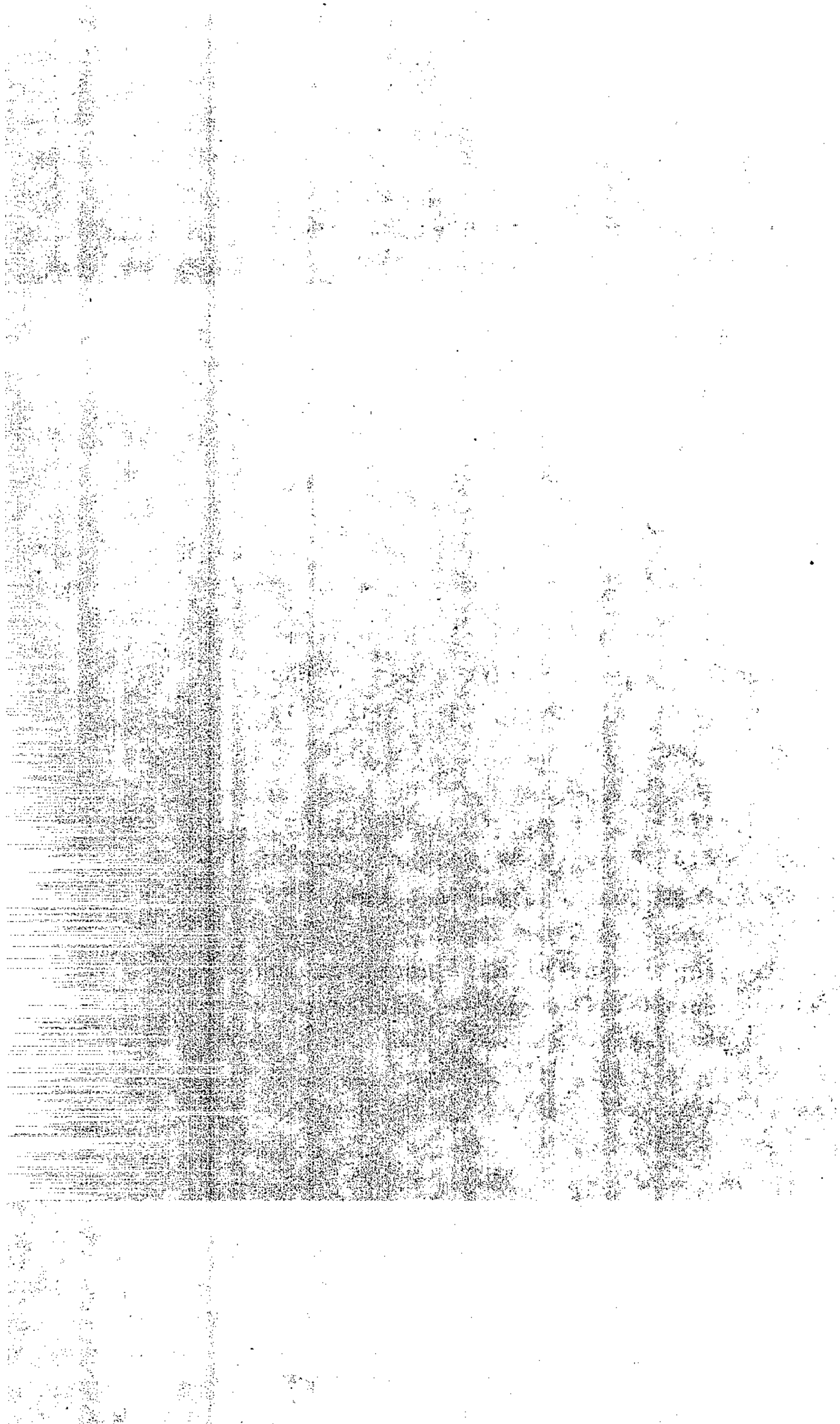
2. Water-based compounds are competitive in price with solvent-based products.

RECOMMENDATIONS

1. Caltrans should field test water-based curing compounds via contract change orders during the period when concrete curing compounds remain exempt from California Air Resources Board guidelines.

2. Caltrans should specify use of water-based curing compounds in Contract Special Provisions when exemption from California Air Resources Board guidelines ends.

3. Caltrans should develop compositional specifications for water-based curing compounds in order to reduce materials costs and to improve quality control.



IMPLEMENTATION

The specification for water-based concrete curing compounds developed on this research project has been submitted to the California Department of Transportation for use on highway construction projects. First use will occur in air pollution control districts which have set limits on volatile organic solvents in protective coatings.

TESTING

Literature Survey

A literature survey made in 1979 indicated that while curing compound formulations based on linseed oil have been evaluated and put into use, very little has been published about the evaluation or use of other types of curing compounds with low volatile organic solvents content.

Obtaining Samples for Testing

Letters explaining the project and requesting product samples were sent to 21 curing compound manufacturers and to 19 suppliers of paint raw materials. The lists of vendors included companies which have furnished such materials to Caltrans and others compiled from FHWA's Special Product Evaluation List.

Preliminary Screening Tests

It was originally intended to test proprietary curing compounds for desired characteristics, and later, follow raw materials manufacturer's recommendations to fabricate and test in-house formulations. Unfortunately, satisfactory proprietary curing compounds were submitted at a very slow pace, and there was insufficient time and manpower available for an in-house development program. Twenty-three proprietary curing compound formulations were screened for conformance to air pollution control regulations and for moisture retention efficiency over portland cement mortar blocks. In a few cases, a manufacturer reformulated his product one or more times in an effort to meet our preliminary requirements. Eight of the products tested met the CARB guidelines and also had satisfactory water retention characteristics. These results are shown in Table 1.

Other Laboratory Tests

During the period of the preliminary screening tests, the following properties of the curing compounds were also determined: density (lbs/gal), drying time, reflectance, viscosity and freeze/thaw resistance. While these properties should not be used as a basis for accepting one type of material in preference to another, they are useful in acceptance testing as indicators of quality control. Results of these tests are shown in Table 2.

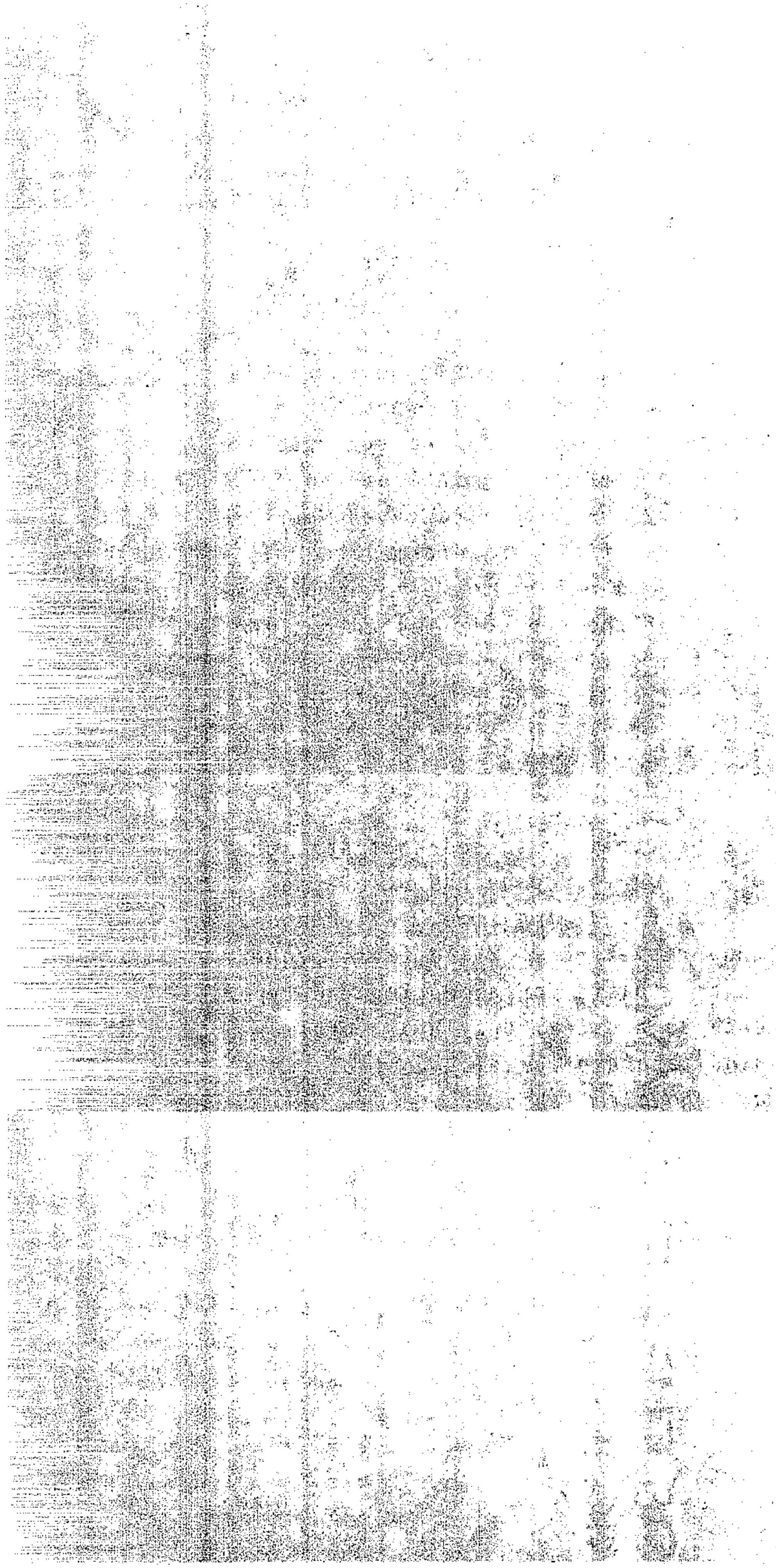


TABLE 1

Proprietary Curing Compound Screening Tests

Product No.	Description*	CARB Guidelines Test[1]	Moisture Retention Test[2]
1	Pigmented Resin Emulsion	Fail	Pass
2	Clear Resin Emulsion	Fail	Fail
3	Clean Linseed Oil Emulsion	Pass	Pass
4	Pigmented Linseed Oil Emulsion	Pass	Pass
5	Emulsified Resin	Fail	Fail
6	Clear Water-Dispersed Linseed Oil	Pass	Pass
7	Clear Water-Reduced Alkyd	Pass	Pass
8	Pigmented Water Soluble Linseed Oil	Pass	Fail
9	Pigmented Water-Based Petroleum Hydrocarbon Resin	Fail	Pass
10	Clear Linseed Oil Emulsion	Pass	Pass
11	Clear Water-Based Resin	Fail	Fail
12	Pigmented Water-Based Resin	Pass	Fail
13	Clear Water-Based Resin	Pass	Fail
14	Pigmented Water-Based Resin	Pass	Fail
15	Clear Water-Based Resin-Wax	Pass	Not Tested[3]
16	Pigmented Water-Based Resin-Wax	Pass	Not Tested[3]
17	Pigmented Anionic Emulsion	Pass	Pass
18	Pigmented Nonionic Emulsion	Pass	Pass
19	Clear Resin Emulsion	Pass	Pass
20	Pigmented Emulsion	Fail	Pass
21	Water-Based Acrylic	Fail	Cracked & Flaked
22	Water-Based with some solvent) Not tested--contained		
23	Water-Based Emulsion) lumps and foamed severely		

[1] Shall contain not more than 250 grams of volatile organic solvent per litre of finished compound, exluding water.

[2] When tested in accordance with California Test Method No. 534, shall not lose more than 6 grams moisture in 24 hours.

[3] Poor storage stability (product curdled).

*Manufacturer's terminology.

TABLE 2

Properties of Proprietary Concrete Curing Compounds

Compound No.	Description	Density Lb/Gal	Viscosity KU	Drying Time/Hrs Set to Touch	Drying Time/Hrs Dry Through	Freeze/Thaw Effect on Viscosity
1	Pigmented Resin Emulsion	8.3-8.6	52-53	1/6-1	1/3-2	--
2	Clear Resin Emulsion	8.24	60	1	2	--
3	Clear Linseed Oil Emulsion	8.0-8.1	55-57	--	--	No change
4	Pigmented Linseed Oil Emulsion	8.5-8.8	57-59		Remained Tacky	--
5	Emulsified Resin	8.3	54	--	--	--
6	Clear Water-Dispersed Linseed oil	8.2	58	--	--	Reduced to 55-56 KU
7	Clear Water-Reduced Alkyd	8.4-8.5	61-63	1	--	Increased to 66-68 KU
8	Pigmented Water Soluble Linseed Oil	8.9	60	--	--	--
9	Pigmented Water-Based Petroleum Hydrocarbon Resin	8.3	59	3/4	--	Reduced to 55-56 KU
10	Clear Linseed Oil Emulsion	8.0	57	Over 24	Over 1 Week	Increased to 64 KU
11	Clear Water-Based Resin	8.1	66	1	Over 24	--
12	Pigmented Water-Based Resin	9.3	78	3	Over 24	Increased to 82 KU
13	Clear Water-Based Resin	8.3	Less than 49	--	--	Curdled
14	Pigmented Water-Based Resin	8.5	Less than 49	--	--	Curdled
15	Clear Water-Based Resin-Wax	8.3	Less than 49	--	--	Curdled
16	Pigmented Water-Based Resin-Wax	8.5	Less than 49	--	--	Curdled
17	Pigmented Anionic Emulsion	9.0	57	1	4	Increased to 60 KU Pigment settled, but was easy to redisperse
18	Pigmented Nonionic Emulsion	9.3	59	1	3	Increased to 61 KU
19	Clear Resin Emulsion	8.2	49	1/2	Remained Soft	Increased to 57 KU Formed gel which could be redispersed
20	Pigmented Resin Emulsion	8.5	50	1/2	Over 24	Increased to 59 KU Formed gel which could be redispersed
21	Water-Based Acrylic	8.5	55	1/6	2/3	--

Performance Tests on Concrete

In the Laboratory

After it had been demonstrated that water-based curing compounds can be made to meet both the Caltrans moisture retention test and the CARB guideline requirements, further tests were made. Four representative formulations were applied to 3"x3"x11" concrete specimens in the laboratory and compared to solvent-based petroleum hydrocarbon resin and chlorinated rubber curing compounds for their influence on strength and abrasion resistance. Untreated concrete specimens were included in the tests as controls. Curing conditions were 73±3°F, 50% relative humidity for seven days. All specimens treated with curing compounds had higher seven-day compressive and flexural strengths and sustained lower abrasion losses than untreated specimens. Each test result shown in Table 3 is the average of values determined for three test specimens. When applied to freshly cast concrete at a rate sufficient to pass the water retention test, water-based curing compounds have approximately the same influence on strength and abrasion resistance as solvent-based materials.

Under Field Conditions

Concrete placed on highway construction jobs is subject to more severe exposure conditions than were the 3"x3"x11" flexural beams in this project. We had hoped to set up an actual test section for comparing the performance of water-based curing compounds with that of solvent-based compounds now in use by Caltrans. Since we did not find a suitable project on which to perform the tests in hot weather, we

TABLE 3

Laboratory Tests of Proprietary Curing Compounds Applied to Concrete

Product No.	Description	Approximate Rate of Application (sq ft/gal)	Flexural Strength (psi @ 7 days)	Compressive Strength (psi @ 7 days)	Abrasion (grams)
		Round 1a - 7 sack concrete			
Control 1	Chlorinated Rubber, Solvent-Based	300	600	5340	14.3
Control 2	Petroleum Hydrocarbon Resin, Solvent-Based	200	600	5840	14.3
3	Clear Linseed Oil Emulsion	Unknown (poor application)	600	5760	7.0
6	Pigmented Linseed Oil Emulsion	200	570	5170	13.0
7	Clear Water-Reduced Alkyd	Unknown (poor application)	670	6030	14.7
		Round 1b - 8 sack concrete			
Control 1	Chlorinated Rubber, Solvent-Based	250	600	5260	13.3
Control 2	Petroleum Hydrocarbon Resin, Solvent-Based	200	670	5840	12.3
3	Clear Linseed Oil Emulsion	100	550	5760	13.7
6	Clear Water-Dispersed Linseed Oil	160	710	5170	11.7
7	Clear Water-Reduced Alkyd	100	510	6030	14.0

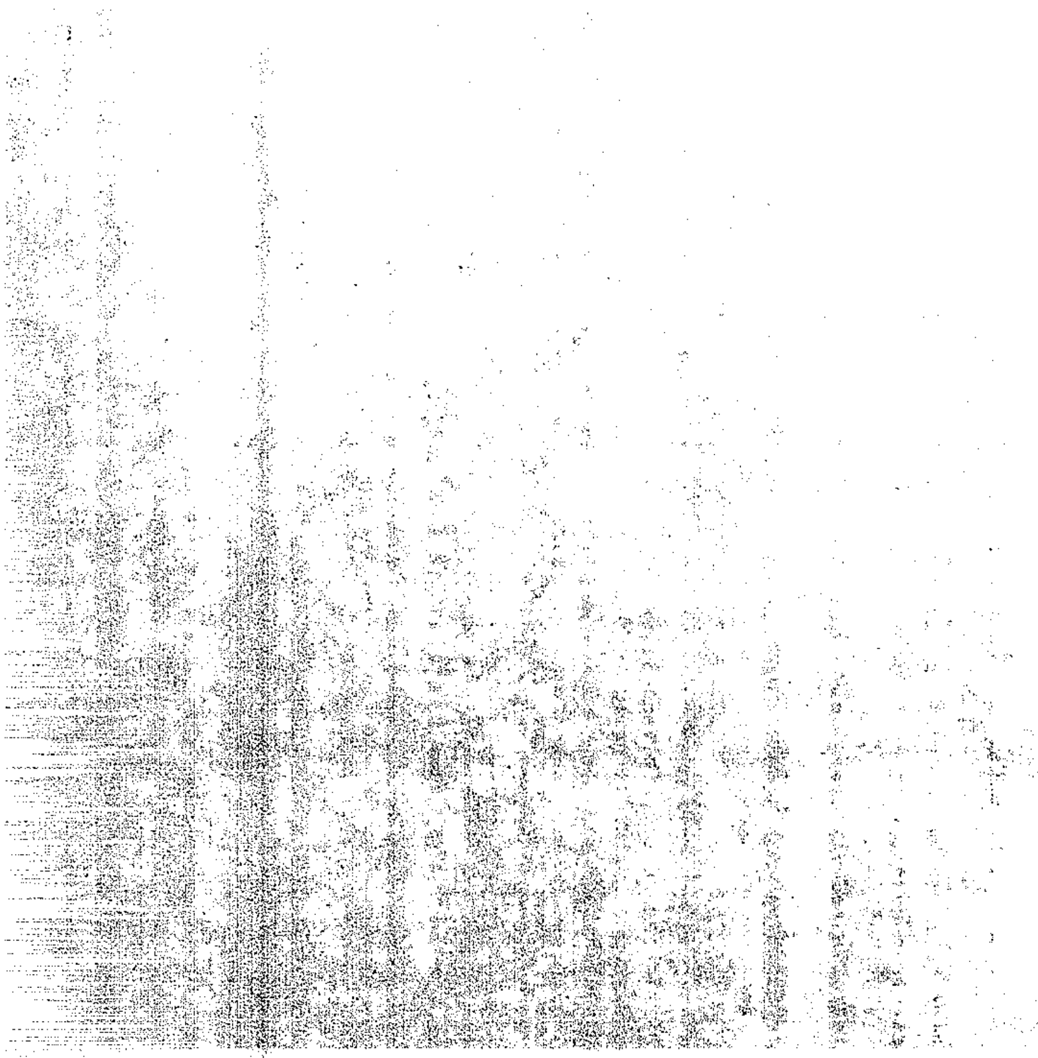


TABLE 3 (Continued)

Laboratory Tests of Proprietary Curing Compounds Applied to Concrete

Product No.	Description	Approximate Rate of Application (sq ft/gal)	Flexural Strength (psi @ 7 days)	Compressive Strength (psi @ 7 days)	Abrasion (grams)
		Round 2 - 8 sack concrete			
Control 1	Chlorinated Rubber, Solvent-Based	330	600	4810	13.7
Control 2	Petroleum Hydrocarbon Resin, Solvent-Based	210	600	5040	10.3
3	Clear Linseed Oil Emulsion	140	540	4710	--
		120	--	--	2.0
4	Pigmented Linseed Oil Emulsion	140	530	4520	--
		160	--	--	6.0
6	Clear Water-Dispersed Linseed Oil	100	580	4630	
		160	--	--	9.0
7	Clear Water-Reduced Alkyd	190	500	4550	10.3
		Round 3 - 8 sack concrete			
Control 1	Chlorinated Rubber Solvent-Based	250	600	4180	--
		330	--	--	14
Control 2	Petroleum Hydrocarbon Resin Solvent-Based	180	550	4220	--
		200	--	--	16
3	Clear Linseed Oil Emulsion	130	500	3900	9
4	Pigmented Linseed Oil Emulsion	170	480	3810	11

prepared an outdoor test slab using 6-sack portland cement concrete. The concrete mix design is shown in Table 4. The dimensions of the slab were 9'x4'x0.75'.

In this field condition test, three pigmented water-based curing compounds were compared with pigmented solvent-based petroleum hydrocarbon resin and chlorinated rubber curing compounds for their effects on the compressive strength and abrasion resistance of 6-sack portland cement concrete. Each compound was applied to a 4'x1.5' area, and a 4'x1.5' strip was left untreated as a control. After 14 days of curing outdoors at temperatures in the range of 70-90°F, six 4-inch diameter x 8-inch deep cores were taken from each strip. Three cores from each set were tested for compressive strength and three were tested for resistance to abrasion. All treated sections had significantly higher compressive strength and lower abrasion losses than the untreated section. There appeared to be no significant difference in performance among the five types of curing compounds. Test results are listed in Table 5. The plan view of the concrete slab in shown in Figure 1, and Figures 2 through 8 show the location of cores taken from each section for testing.

OTHER CONSIDERATIONS

The solvent-based and water-based curing compounds which were compared on the outdoor test on a 4'x9' concrete slab were all furnished by one supplier. The supplier also

TABLE 4

Concrete Mix Design for Outdoor Test Slab

Concrete Mix Design (6-sack mix, 0.5 water/cement ratio)

Water, lbs	283
Cement, lbs	564
Concrete sand, lbs	1269
1" x #4 coarse aggregate, lbs	1968

Aggregate Gradings

Sieve Size	Concrete Sand Percent Passing	1" x #4 Percent Passing
1-1 1/2"		100
1"		98
3/4"		78
1/2"		30
3/8"	100	12
#4	97	0.4
#8	84	
#16	66	
#30	40	
#50	20	
#100	6	
#200	2.3	

TABLE 5

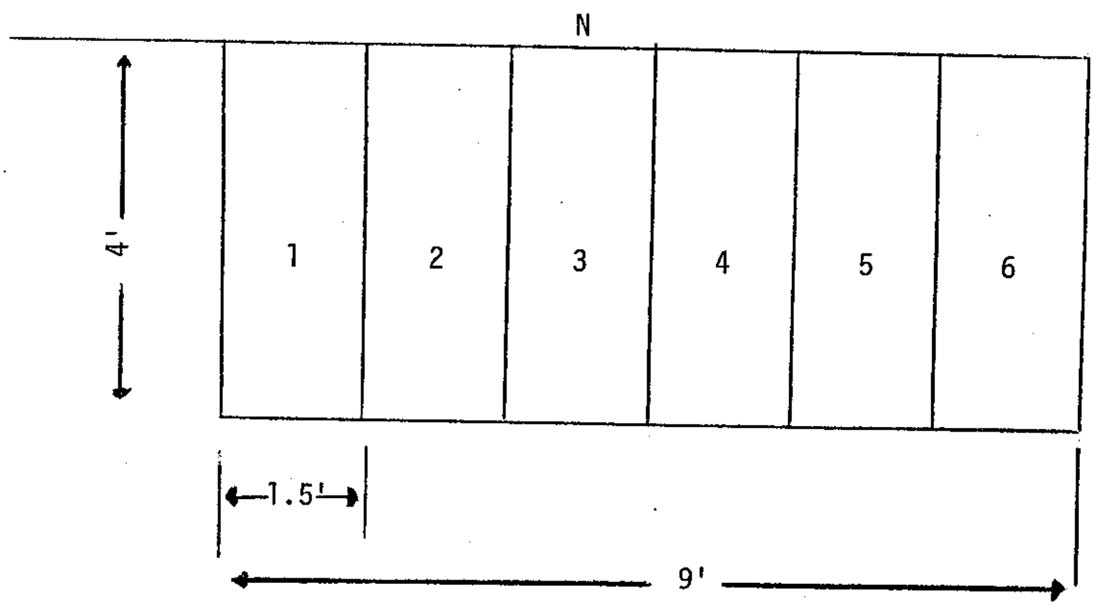
Performance Tests of Proprietary Curing Compounds Applied to Concrete Under Field Conditions (70°-90°F)

Section	Compound No.	Description	Rate of Application sq ft/gal	Compressive Strength* psi @ 14 days	Abrasion* loss, grams
1	Control 1	Chlorinated Rubber, Solvent-Based	300	4560	15
2	4	Pigmented Linseed Oil Emulsion	200	4470	13
3	17	Pigmented Anionic Emulsion	200	4625	14
4	Control 2	Petroleum Hydrocarbon Resin, Solvent-Based	200	4635	13
5	18	Pigmented Nonionic Emulsion	200	4690	15
6	Control 3	No Treatment	--	3845	28

*Average of 3 test specimens

FIGURE 1

PLAN OF CONCRETE TEST SLAB



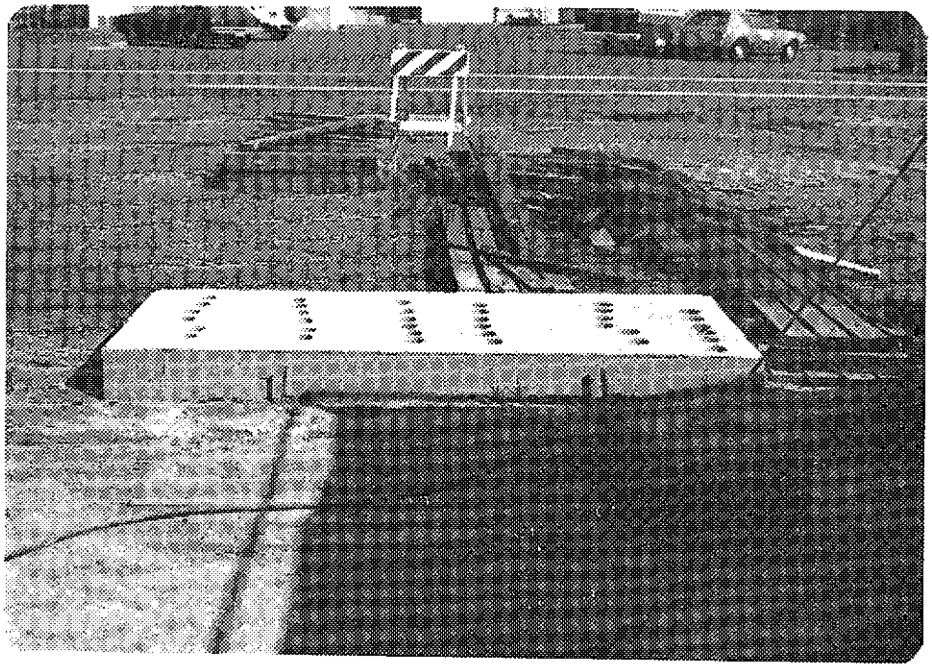
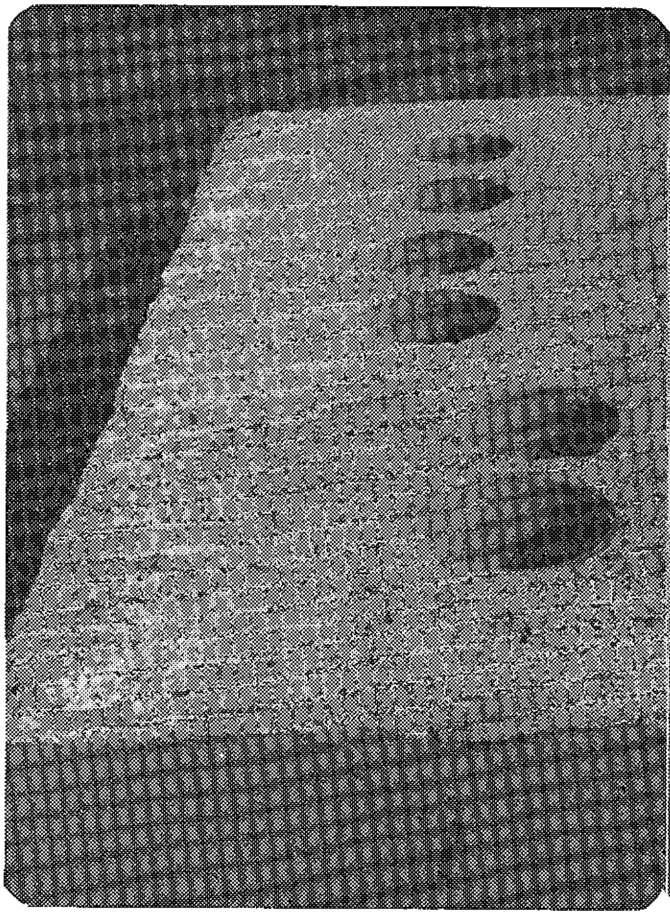


Figure 2



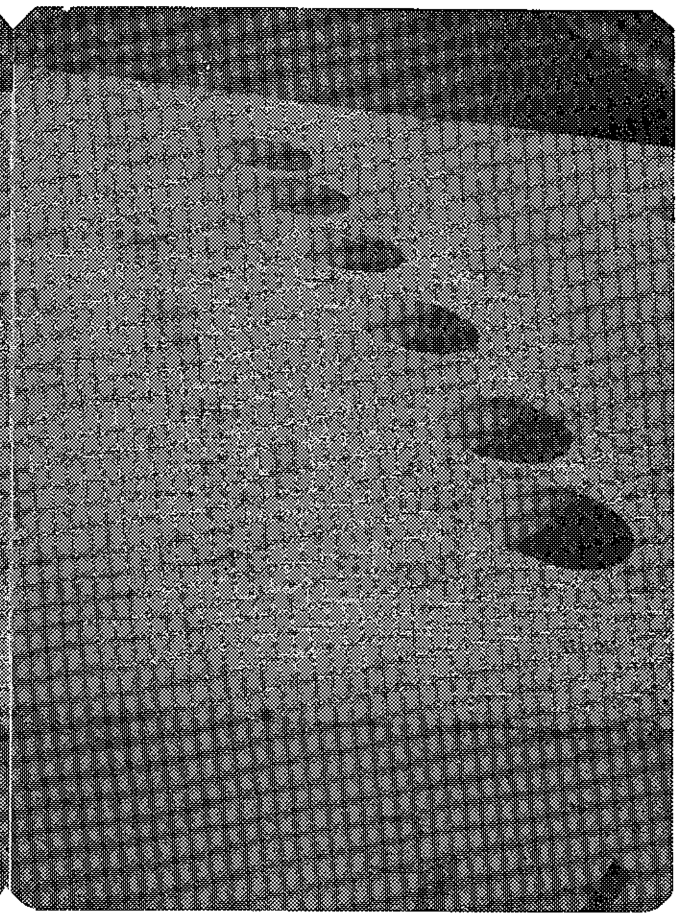


Figure 3

Figure 4

Views of Test Slab After Curing and Coring

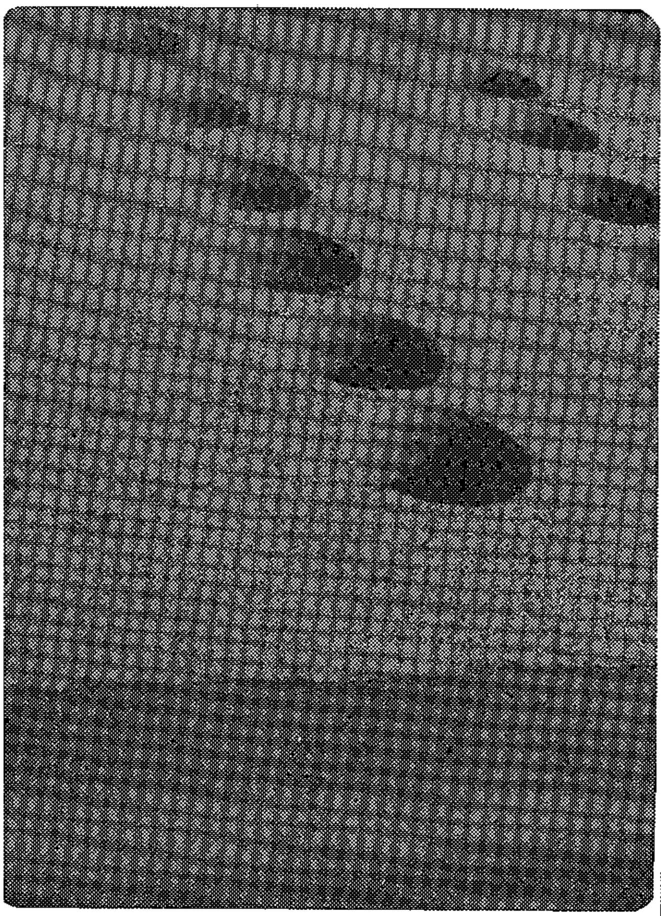


Figure 5

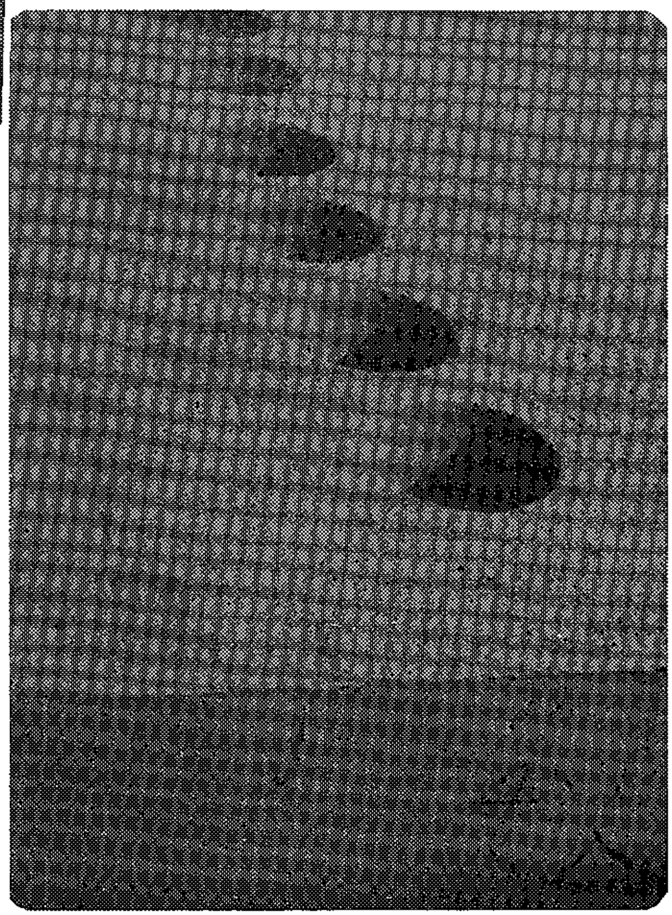
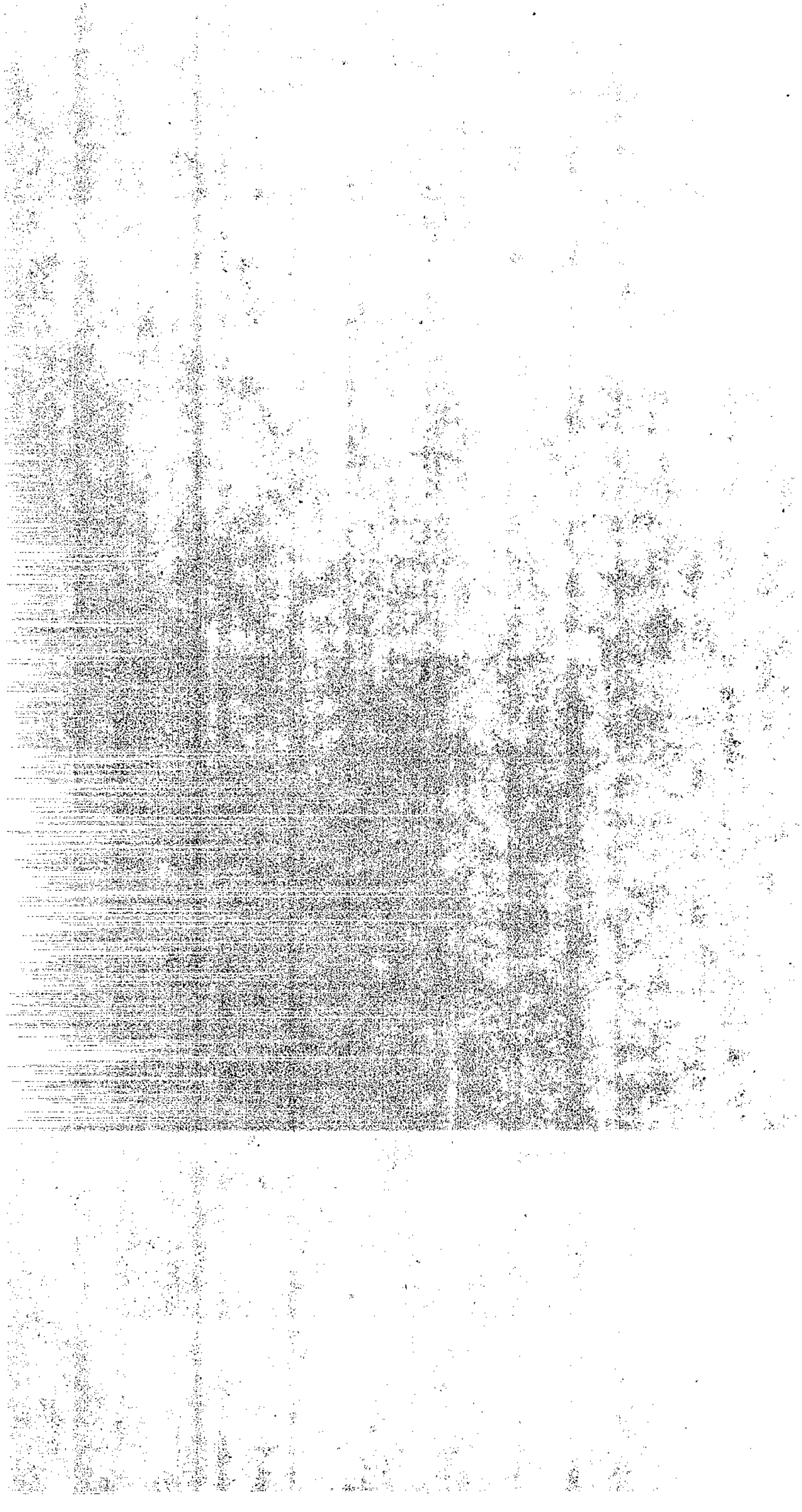


Figure 6

Views of Test Slab After Curing and Coring



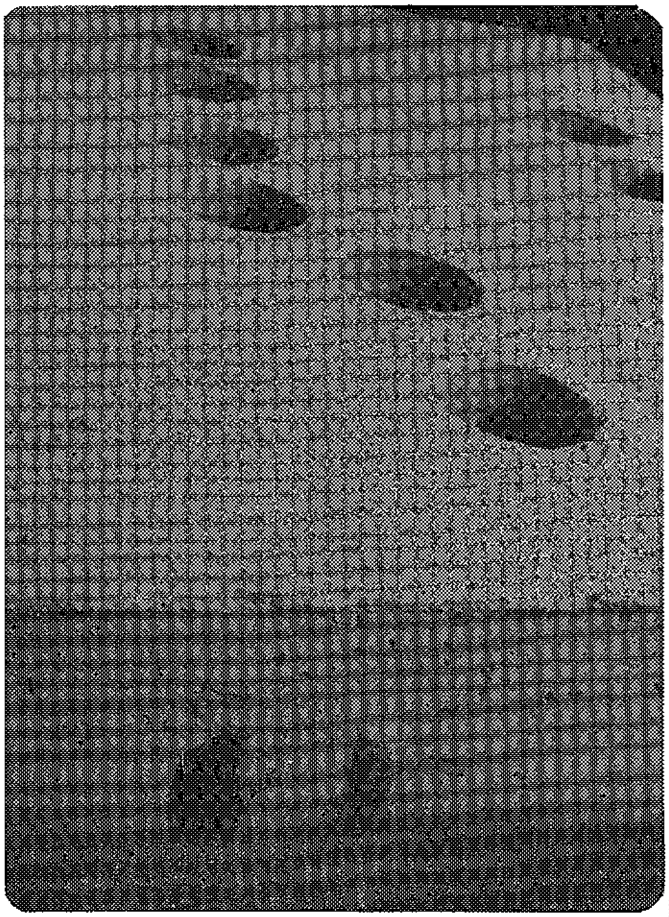


Figure 7

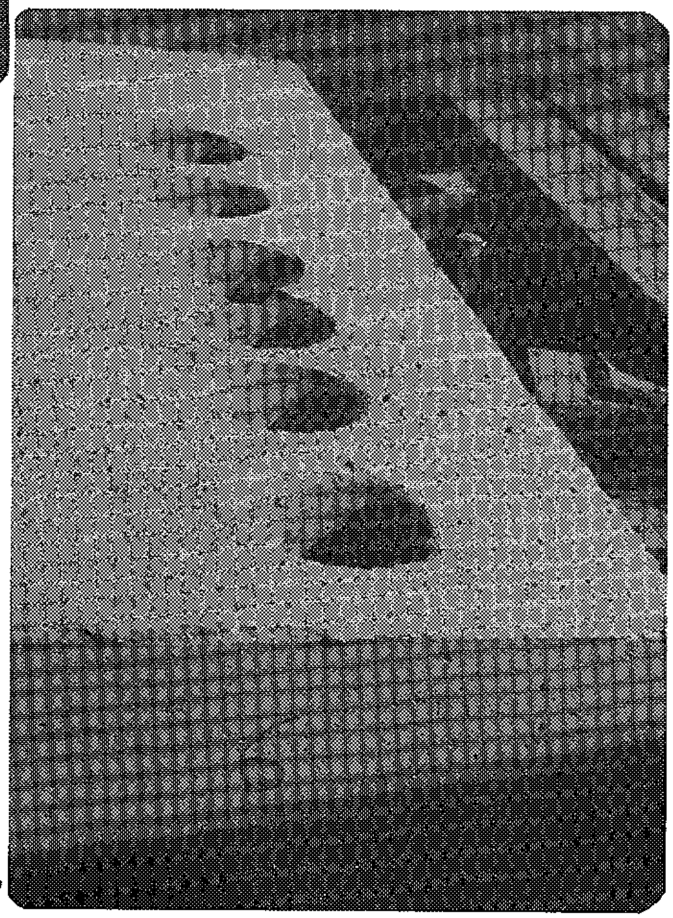
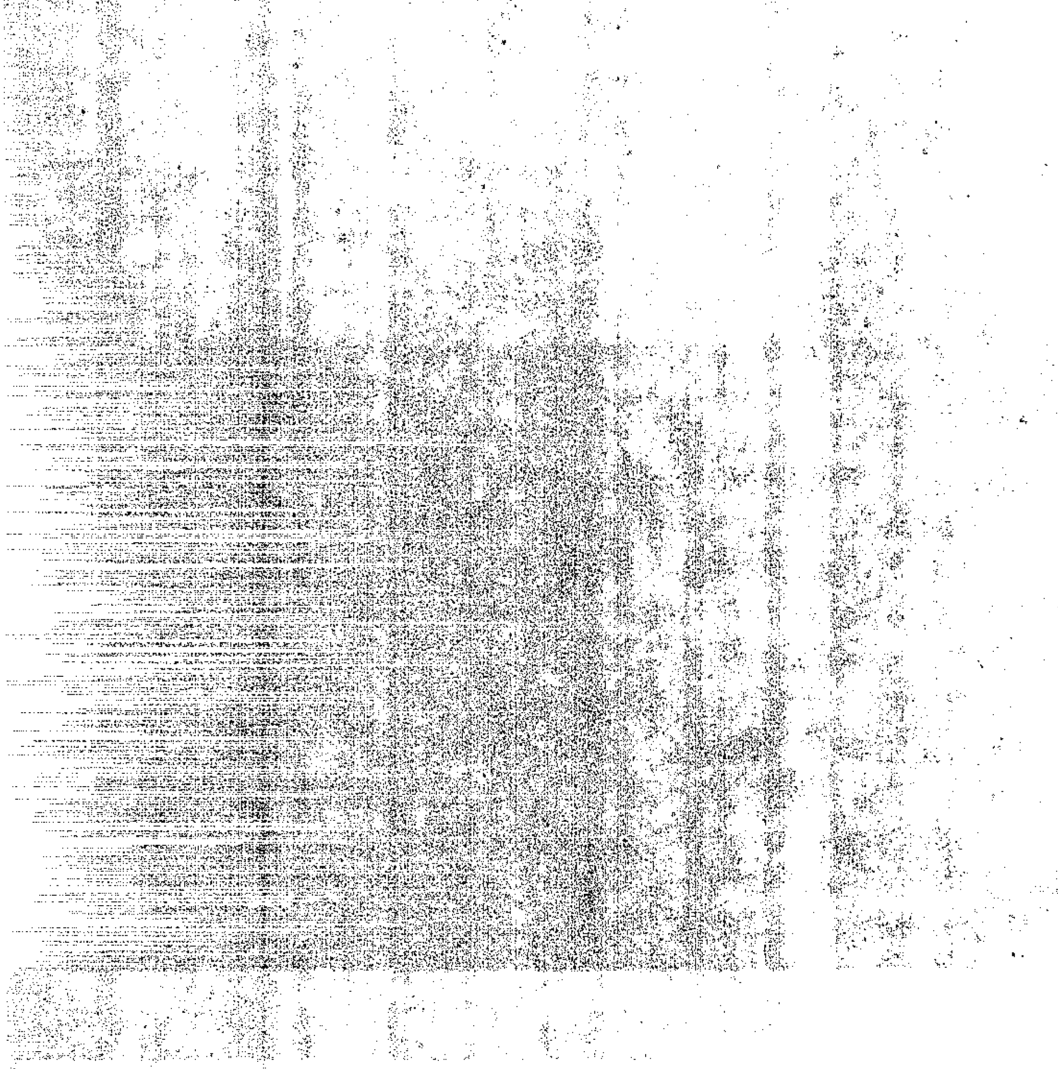


Figure 8

Views of Test Slab After Curing and Coring



submitted an estimate of the prices he would charge a distributor for furnishing each type of material in 55-gallon drums. The materials cost per gallon for the linseed oil emulsion curing compound was about 35% lower than that for the solvent-based petroleum hydrocarbon curing compound. The cost of the other water-based compounds was 5 to 8% lower, and the materials cost of the solvent-based chlorinated rubber curing compound was 60% higher. Since the chlorinated rubber compound is applied at the rate of 300 sq ft/gallon, while the other materials are applied at 200 sq ft/gallon, the materials cost as used is only 6% higher for chlorinatd rubber than for the petroleum hydrocarbon resin. The relative materials costs are shown in Table 6.

Since we were able to use the same equipment and procedure for applying all the compounds tested, it is apparent that use of water-based compounds will require no costly modifications from present methods.

Current Caltrans specifications require the use of the chlorinated rubber type curing compounds in situations, e.g., median barriers, where a durable weather-resistant paint-like coating is desired for aesthetic reasons. In general, water-based curing compounds may be expected to form coatings of the same durability as that of solvent-based compounds made from similar resins.

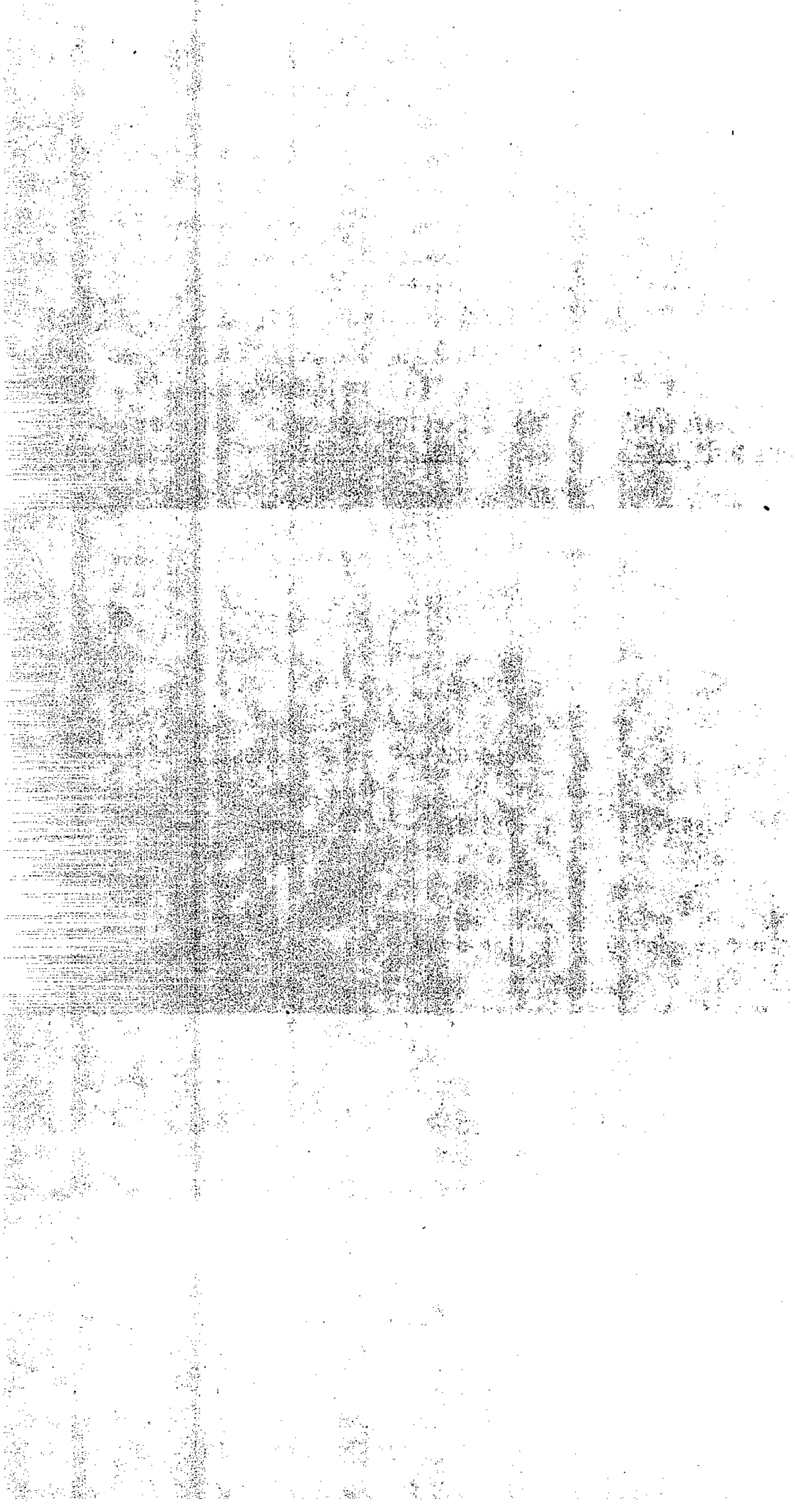
None of the water-based compounds tested under this project are as durable as chlorinated rubber. Water-based acrylic systems, which are costlier than other water-based material, may be expected to compare in durability with chlorinated rubber. To date, however, we have tested no acrylics which have suitable water retention characteristics.

TABLE 6

Estimated Relative Materials Cost of Solvent-Based
and Water-Based Curing Compounds

Compound	Est. Cost/Gallon (Materials Cost)*	Est. Cost/Sq Ft (Materials Cost)	
		@ 200 sq ft/gal	@ 300 sq ft/gal
Petroleum Hydrocarbon Resin (solvent-based)	$5.80	$0.029	--
Anionic (water-based)	5.35	0.0268	--
Nonionic (water-based)	5.50	0.0275	--
Chlorinated Rubber (solvent-based)	9.25	0.0462	0.0308
Linseed Oil Emulsion (water-based)	3.66	0.0183	--

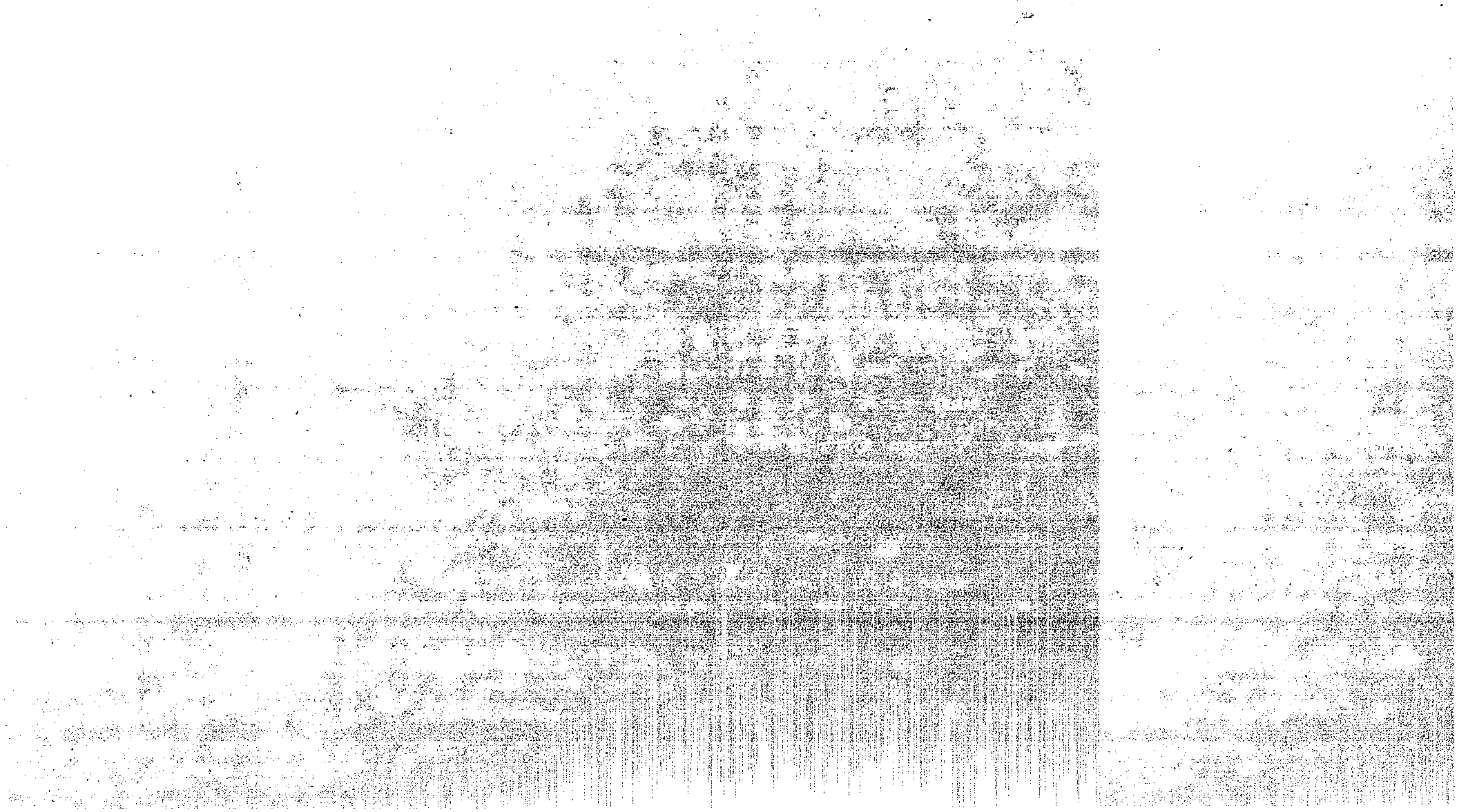
*Cost to the distributor when furnished in 55-gallon drums



SPECIFICATION DEVELOPMENT

Test values of curing compounds measured on this project were used in drafting a tentative specification for water-based curing compounds (see Appendix). Caltrans formulation specifications for solvent-based curing compounds allow minimum total solids contents of from 49.5 to 58.2%. Although water-based formulations are similar in properties to solvent-based formulations, it was decided to lower the total solids requirement to 35% minimum because one of the better performing water-based formulations contains only 36.5% total solids. Experience with both solvent-based and water-based formulations indicates that at least 7% pigment is required to meet the reflectance requirements in Caltrans, ASTM and AASHTO specifications.

The new viscosity requirement approximates that of the current solvent-based formulations. A lower limit on viscosity has been added to minimize drainage from sloping surfaces. Although the water retention characteristics now required of solvent-based curing compounds can be met by water-based formulations, the allowable water loss at 24 hours was increased from six grams to eight grams in order to conform more closely to the loss permitted by ASTM and AASHTO specifications which are familiar to manufacturers outside the State of California.



BIBLIOGRAPHY

1. Best, C. H., Crary, J. F., Gast, L. E. and W. L. Kubie. Linseed oil formulations as curing compounds for antiscaling compounds for concrete. Transportation Research Board, Washington, D.C., 1974, pp. 63-70 (Transportation Research Record 504).

2. Heskin, R. A. A study of coatings based on water soluble linseed oil, to be used as a concrete curing membrane. North Dakota State University, Fargo, ND, 1970, NTIS PB 192483.

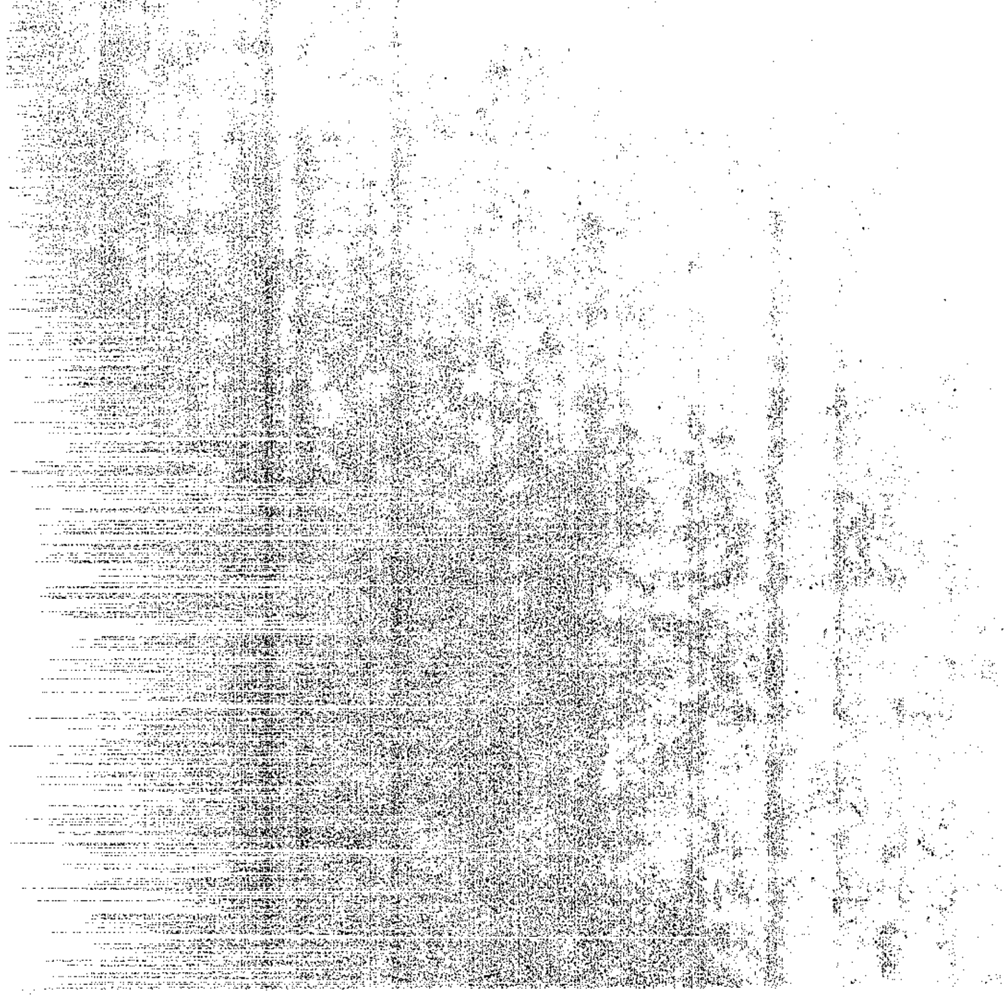
3. Derrington, C. F. Investigation of colorless and water-based concrete curing compounds. U.S. Army Waterways Experiment Station, Vicksburg, MS, June 1969 (Technical reports C-69=7).

4. Rice, C. E. Linseed oil based compound used for curing concrete. Public Works, Vol. 101, No. 2, February 1970: 71-72.

5. Heskin, R. A. and A. E. Rheinecke, A study of coatings based on linseed oil to be used as a concrete curing membrane. North Dakota University, Fargo, ND, March 26, 1967.

6. Kriegel, Robert F. Laboratory evaluation of linseed oil emulsion as a curing agent for portland cement concrete. Texas Highway Department, Austin, TX, September 1971.

APPENDIX



Tentative Specification for Pigmented Water-based Curing Compound

Pigmented curing compound shall be a water-based emulsion or suspension consisting of resins, latexes, or drying oils with co-solvents, pigments, extenders, suspending agents, and other additions as needed to obtain a product meeting all state and local air pollution control requirements in effect in California and having the following characteristics:

Total solids, by weight percent	35, minimum
Pigment, by weight, percent	7, minimum
Viscosity at 77°F, KU	50-65
Daylight reflectance, percent (ASTM: E97)	60, minimum
Water retention, grams net loss at 24 hrs-	8, maximum
grams net loss at 72 hrs-	23, maximum
Dry time at 77°F, 50% relative humidity, 6 mil wet film thickness-	
Set to touch, hours	1 maximum
Dry through, hours	4 maximum
Freeze-thaw resistance, ASTM-D2243, change in viscosity after freeze-thaw cycling, percent of original KU	10 maximum

The vehicle solids shall be organic materials; inorganic film-forming materials, such as silicates, will not be acceptable,

STATE OF CALIFORNIA
DEPARTMENT OF TRANSPORTATION
DIVISION OF FACILITIES CONSTRUCTION
OFFICE OF TRANSPORTATION LABORATORY

The Effect of Fibers and Rubber on the Physical Properties of Asphalt Concrete

FTV

Study Supervised by .... Robert N. Doty, P.E.

Principal Investigator .... Roger Smith, P.E.

Co-Principal Investigators .... Jack L. Van Kirk, P.E.
Thomas Scrimsher, P.E.

Report Prepared By .... Jack L. Van Kirk, P.E.

RAYMOND A. FORSYTH, Chief
Office of Transportation Laboratory

85-18

82-18

TECHNICAL REPORT STANDARD TITLE PAGE

1. REPORT NO.	2. GOVERNMENT ACCESSION NO.	3. RECIPIENT'S CATALOG NO.
CA/TL-85/18		

4. TITLE AND SUBTITLE	5. REPORT DATE
The Effect of Fibers and Rubber on the Physical Properties of Asphalt Concrete	June 1986
	6. PERFORMING ORGANIZATION CODE
7. AUTHOR(S)	8. PERFORMING ORGANIZATION REPORT NO.
Jack L. Van Kirk	643374
9. PERFORMING ORGANIZATION NAME AND ADDRESS	10. WORK UNIT NO
Office of Transportation Laboratory California Department of Transportation Sacramento, California 95819	11. CONTRACT OR GRANT NO. F84TL61
12. SPONSORING AGENCY NAME AND ADDRESS	13. TYPE OF REPORT & PERIOD COVERED
California Department of Transportation Sacramento, California 95807	Final
	14. SPONSORING AGENCY CODE

15. SUPPLEMENTARY NOTES

16. ABSTRACT

This report describes the laboratory testing and a field installation of several fiber and rubber additives which, when used in asphalt concrete, purportedly provide resistance to reflection cracking and surface abrasion by tire chains. The products tested were Boni-Fibers, Fiber Pave 3010 fibers, Marvess Olefin fibers, Ramflex crumb rubber, G-274 crumb rubber, ARS (Arm-R-Shield) rubberized AC, and PlusRide rubberized AC. The three fibers and the Ramflex crumb rubber were placed in the field installation.

Specifically, the report covers laboratory testing, construction and coring of field test sections, laboratory testing of construction and core samples, and performance of the test sections for the first year.

17. KEY WORDS	18. DISTRIBUTION STATEMENT
Fiber, rubberized asphalt, crumb rubber, AC overlays, asphalt concrete, reflection cracking, surface abrasion	No restrictions. This document is available to the public through the National Technical Information Service, Springfield, VA 22161.

19. SECURITY CLASSIF. (OF THIS REPORT)	20. SECURITY CLASSIF. (OF THIS PAGE)	21. NO. OF PAGES	22. PRICE
Unclassified	Unclassified		

DS-TL-1242 (Rev.6/76)

NOTICE

The contents of this report reflect the views of the Office of Transportation Laboratory which is responsible for the facts and the accuracy of the data presented herein. The contents do not necessarily reflect the official views or policies of the State of California or the Federal Highway Administration. This report does not constitute a standard, specification, or regulation.

Neither the State of California nor the United States Government endorse products or manufacturers. Trade or manufacturers' names appear herein only because they are considered essential to the object of this document.

CONVERSION FACTORS

English to Metric System (SI) of Measurement

Quality	English unit	Multiply by	To get metric equivalent
Length	inches (in)or(")	25.40 .02540	millimetres (mm) metres (m)
	feet (ft)or(')	.3048	metres (m)
	miles (mi)	1.609	kilometres (km)
Area	square inches (in^2) square feet (ft^2) acres	6.432×10^{-4} .09290 .4047	square metres (m^2) square metres (m^2) hectares (ha)
Volume	gallons (gal) cubic feet (ft^3) cubic years (yd^3)	3.785 .02832 .7646	litre (l) cubic metres (m^3) cubic metres (m^3)
Volume/Time (Flow)	cubic feet per second (ft^3/s	28.317	litres per second 1/s)
	gallons per minute (gal/min)	.06309	litres per second (1/s)
Mass	pounds (lb)	.4536	kilograms (kg)
Velocity	miles per hour (mph) feet per second (fps)	.4470 .3048	metres per second (m/s) metres per second (m/s)
Acceleration	feet per second squared (ft/s^2)	.3048	metres per second squared (m/s^2)
	accéleration due to force of gravity (G) (ft/s^2)	9.807	metres per second squared (m/s^2)
Density	(lb/ft^3)	16.02	kilograms per cubic metre (kg/m^3)
Force	pounds (lbs) (1000 lbs) kips	4.448 4448	newtons (N) newtons (N)
Thermal Energy	British termal unit (BTU)	1055	joules (J)
Mechanical Energy	foot-pounds (ft-lb) foot-kips (ft-k)	1.356 1356	joules (J) joules (J)
Bending Moment or Torque	inch-pounds (in-lbs) foot-pounds (ft-lbs)	.1130 1.356	newton-metres (Nm) newton-metres (Nm)
Pressure	pounds per square inch (psi) pounds per square foot (psf)	6895 47.88	pascals (Pa) pascals (Pa)
Stress Intensity	kips per square inch square root inch ($ksi\sqrt{in}$)	1.0988	mega pascals$\sqrt{metre}$ ($MPa\sqrt{m}$)
	pounds per square inch square root inch ($psi\sqrt{in}$)	1.0988	kilo pascals$\sqrt{metre}$ ($KPa\sqrt{m}$)
Plane Angle	degrees (°)	0.0175	radians (rad)
Temperature	degrees fahrenheit (F)	$\frac{+F - 32}{1.8} = +C$	degrees celsius (°C)

ACKNOWLEDGEMENTS

The author wishes to express appreciation and acknowledge the many individuals who were involved in the completion of various aspects of this project:

Ken Iwasaki Ron Morrison Laurie Davis Jayne Robinson (TransLab)	Laboratory Testing and Data Assembly
Rui Maeda Ernest Elmore (TransLab)	Aggregate Testing
Lydia Burgin Marti Corralejo	Word Processing
Irene Itamura John Leonhardt Rick Liptak Doug Jones Guy Buckman (Dist. 03 Construction)	District Design General Field Construction Assistance and Materials Sampling

TABLE OF CONTENTS

TABLE OF CONTENTS (Continued)

LIST OF TABLES

LIST OF FIGURES

I. INTRODUCTION

This report describes the product evaluation laboratory testing and field installation of several asphalt concrete pavement modifiers (fiber and rubber) purported to provide resistance to reflection cracking, and surface abrasion by tire chains.

The products tested and their suppliers are listed below:

- BoniFibers, Type B (Kapejo)
- Fiber Pave 3010 Fibers (Hercules)
- Marvess Olefin Fibers (Phillips)
- ARS (Arm-R-Shield) Rubberized Binder (Arizona Refining)
- Ramflex Crumb Rubber (Genstar)
- G-274 Crumb Rubber (Genstar)
- PlusRide Rubberized AC (All Seasons Surfacing now PlusRide Asphalt Inc.)

The report covers product evaluation laboratory testing, construction and coring of field test sections, laboratory testing of construction and core samples, and performance of the test sections for the first year.

II. BACKGROUND

California has been faced for some time with the problem of how to rehabilitate the badly cracked and abraded portland cement concrete (PCC) pavement on I-80 in the snow belt of the Sierra Nevada mountains. The high elevation (7200 foot summit) and climate extremes create a freeze-thaw action which, over the years, has cracked the PCC pavement.

Much of the pavement, which was completed in 1964, is cracked, but still considered to be structurally adequate. However, the surface has been badly abraded and polished by tire chains which are frequently required during the winter months.

Attempts to rehabilitate this PCC pavement using conventional asphalt concrete (AC) overlays have often proven unsuccessful. Conventional AC, which is used in this area in thicknesses of 0.2 feet or greater, does not hold up under the heavy truck traffic and tire chain action.

A possible solution to this problem is to modify the conventional AC mix with fibers or rubber to create a more durable AC pavement. This study was therefore undertaken to determine the effect of fiber or rubber additives on the physical properties of AC in both the laboratory and in a field test section.

A proposed 1984 project, involving an overlay of PCC on I-80 east of Truckee, California, near Floriston (Figure 1), was selected for the installation of AC overlay test sections containing fiber-modified and rubber-modified AC. In addition to the test sections, a control section of conventional AC was included for performance comparison. Prior to field installation, lab testing was needed to determine which mixes to place as test sections, and to establish an optimum asphalt content for each experimental mix.

Thus, the objective of this research was to determine, by lab and field testing, if the addition of polypropylene fibers, polyester fibers, or rubber to an AC mixture will provide the improved flexibility and/or toughness needed to resist reflection cracking and surface abrasion.

III. CONCLUSIONS

1. The addition of fibers or rubber to ashalt concrete mixes improves the surface abrasion resistance (California Test 360, Method B) in most cases.

2. The ARS and PlusRide rubberized AC mixes had by far the best surface abrasion resistance in laboratory tests.

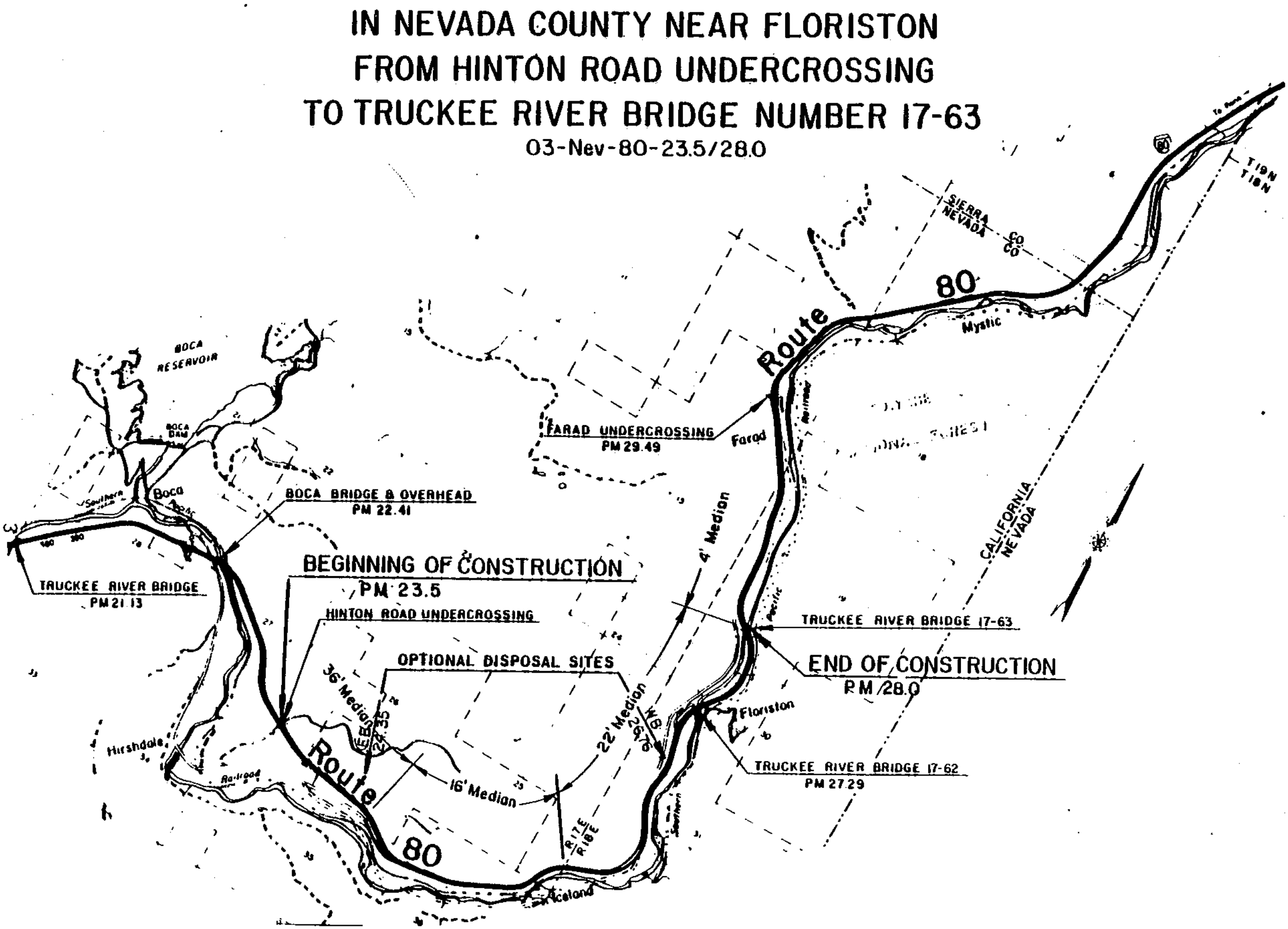


Figure 1 - Location Map

3. The effect that a certain fiber or rubber additive has on asphalt concrete mix properties may vary with aggregate source.

4. All rubber modified AC mixes exhibited lower Hveem stability values then the conventional mix, with the PlusRide mix exhibiting an extremely low value.

5. All fiber and rubber modified AC mixes except the ARS require higher asphalt contents compared to conventional mixes.

6. Due to the relatively low melting temperature of polypropylene, the polypropylene fiber mixes require lower batching temperatures than those normally used for conventional mixes in cool climates.

IV. RECOMMENDATIONS

1. Fiber and rubber modified AC mixes should be placed in other experimental field installations.

2. Fiber and rubber modified AC mixes should only be used on an experimental basis until an adequate time has passed to properly evaluate their long-term performance.

3. A method for determining the relative amounts of asphalt and rubber in a rubberized AC mix should be developed through a research effort.

V. IMPLEMENTATION

The findings of this research were partially implemented by recommending which fiber and rubber modified AC mixes should be field tested on the 1984 Floriston overlay project. (See Appendices B and C).

Further implementation will consist of recommending that fiber and rubber modified AC mixes be tested on future California highway projects.

In general, the knowledge gained from working with these relatively new products will be useful in future Caltrans involvement with these or similar technologies.

VI. PRODUCT EVALUATION LABORATORY TESTING

A. Background

Testing of several of the experimental additives was conducted by Caltrans District 03 Materials Laboratory in Marysville using aggregate from source A Then, because of staff reductions, it was decided to transfer the responsibility for testing from the district to the Transportation Laboratory (TransLab) in Sacramento. It was also decided to expand the testing program to encompass an additional fiber (Marvess Olefin 60 denier) and an additional rubber product (PlusRide). This additional testing, and some unanticipated technical problems with testing some of the modified mixes, created a shortage of aggregate from source A. Thus it was necessary to obtain a new and larger aggregate sample (from source B) and repeat the partially completed testing program to provide a complete set of data representing one aggregate source for all the mixes tested.

B. Fiber and Rubber Products Tested

Four fiber and four rubber modified mixes, each having different properties, were tested in the lab. They are listed below with their manufacturers.

- BoniFiber, Type B, Kapejo
- Fiber Pave 3010, Hercules
- Marvess Olefin (16 Denier), Phillips
- Marvess Olefin (60 Denier), Phillips
- Ramflex Crumb Rubber, Genstar
- G-274 Crumb Rubber, Genstar
- ARS Rubberized Binder, Arizona Refining
- PlusRide Rubberized AC, All Seasons Surfacing (now PlusRide Asphalt Inc.)

A conventional AC mix was also tested for comparison purposes. All mixes contained 1/2-inch maximum medium, Type A, aggregate (Caltrans Standards Specifications, 1984) and Chevron AR-4000 asphalt.

The four fibers and two crumb rubbers were each added "dry" to the hot dry aggregate at rates recommended by the manufacturers. After dry mixing for about three seconds, the asphalt was added, and this combination mixed until well blended. The two rubberized asphalt mixes are patented processes and were produced according to their respective formulas.

1. BoniFiber, Type B

BoniFiber is a white, 1/4-inch long polyester fiber supplied by Kapejo, Inc., of Wilmington, Delaware. It is a 4.1 denier* fiber with a melting point of about 480°F.

* Denier - The weight in grams of 9000 meters of the fiber.

2. Fiber Pave 3010 Fiber

Fiber Pave 3010 is a white 3/8-inch long polypropylene fiber supplied by Hercules, Inc., of Wilmington, Delaware. It is a 15 denier fiber with a melting point of about 320°F.

3. Marvess Olefin Fiber

Marvess Olefin is a white 1/2-inch long polypropylene fiber supplied by Phillips Fibers Corp., of Greenville, South Carolina. It has a melting point of about 320°F. Two Marvess Olefin fibers were tested with the only difference being the denier (and therefore, the strength) of the fiber. A 16 and a 60 denier fiber were tested, with the 16 denier fiber having superior tensile strength.

4. Ramflex Crumb Rubber

Ramflex is a dry, powdered, free-flowing reclaimed tire rubber. It is reclaimed using the patented Reclaimator process by GSX Polymers of Vicksburg, Mississippi, a Division of Genstar (formerly U.S. Rubber Reclaiming Co., Inc. of Buffalo, New York). This process produces a devulcanized rubber which mixes quite readily with AC.

5. G-274 Crumb Rubber

G-274 crumb rubber is a combination of vulcanized, devulcanized, and natural rubbers. The combination is dry and free flowing, and consists of mostly ground vulcanized rubber. It is produced by Genstar Corp. of Phoenix, Arizona.

6. ARS (Arm-R-Shield) Rubberized Binder

ARS is a patented rubberized binder that is a combination of ground reclaimed rubber, extender oil and asphalt. These ingredients are blended and "cooked" using special equipment at the plant site. The binder is then generally transferred to one of the plant's asphalt storage tanks and used in the same manner as conventional asphalt. The ARS binder is produced by Arizona Refining Co. of Phoenix, Arizona.

7. PlusRide Rubberized AC

PlusRide is a patented process which utilizes a coarsely chopped (1/4" x #10) and a granulated (#10 x #40) tire rubber in conjunction with a gap-graded aggregate. When the rubber and the aggregate are combined, the result is a uniform grading. Due to the high rubber content (3% by weight of total mix), the asphalt demand (7.5 - 9.5% by weight of total mix) is much higher than for a conventional mix.

Information on this patented mix can be provided by PlusRide Asphalt Inc., Bellevue, Washington. The mix originated in Sweden and has reportedly been used there successfully for more than 15 years.

C. Materials Testing - Aggregate Source A

Aggregate from source A, Teichert's Donner Pit, was a relatively nonabsorbtive pit-run gravel having a specific gravity of 2.61. As discussed earlier (Section VI-A), only a portion of the testing was completed using this aggregate. For this reason, only the surface abrasion results will be discussed here. (Results are compared in Section E to results obtained using aggregate from source B.)

All mixes tested showed an improvement in surface abrasion loss (California Test 360, Method B) when compared to the conventional mix (Table 1). The ARS rubberized mix showed the lowest loss, by far, with only 13.2 grams. This was anticipated due to earlier experience with this product(1)*. The three fibers and G-274 crumb rubber showed a moderate improvement whereas the Ramflex crumb rubber showed only a slight improvement over the

* Reference

TABLE 1

SURFACE ABRASION LOSS DATA (Aggregate A[1])

ADDITIVE	OPTIMUM BITUMEN CONTENT (OBC)[3] (%)	SURFACE ABRASION LOSS[4] (gm)
Control (Conv. mix)	6.7	33.0
Ramflex (1.0%)[2] Crumb Rubber	7.0	30.4
BoniFibers (0.25%)	7.0	26.2
Fiber Pave 3010 (0.3%)	7.0	26.7
Marvess Olefin (0.4%) (16 Den)	7.0	25.7
G-274 (1.0%) Crumb Rubber	7.0	27.6
ARS (Arm-R-Shield)	8.0[5]	13.2

Notes:
1. 1/2" maximum medium Type A.
2. All percentages are by dry weight of aggregate.
3. California Test 367.
4. California Test 360, Method B.
5. This is a binder which contains 76% asphalt, 20% rubber and 4% extender oil. Considering asphalt only, it was 6.1%, by dry weight of aggregate.

conventional AC. These results indicate that the addition of any of these fibers or rubbers might improve the resistance to surface abrasion in the field.

D. Materials Testing - Aggregate Source B

Aggregate from source B, State Donner Pit, was very similar to aggregate from source A, a relatively nonabsorbtive pit-run gravel. Data on aggregate B are shown in Table 2 (including mix design data). Using the mixing procedure outlined in Section B, mixes containing each additive were prepared and evaluated by means of the following tests:

1. Optimum Bitumen Content (O.B.C.) (California Test 367)
2. Hveem Stability (California Test 366)
3. Surface Abrasion (California Test 360, Method B)
4. Specific Gravity (California Test 308)
5. Cohesion (California Test 306)
6. Resilient Modulus (M_r) (Chevron Method)

A summary of the test results is shown in Table 3. Complete data are located in Appendix A. Data for a conventional mix with no additives are shown for comparison purposes.

1. Optimum Bitumen Content (O.B.C.) (California Test 367)

The first testing conducted was to determine the OBC for the control and all other mixes. In general, the fiber mixes required an asphalt content about 0.5% higher than the control. Since the fibers are nonabsorptive, the extra asphalt was required only to coat the fibers in the mix. The rubber mixes, however, (excluding the ARS mix) required even more asphalt, up to 1.1% higher than the control. Supposedly, this extra asphalt not only coats the rubber particles in the mix, but is also partially absorbed into the rubber.

TABLE 2

MATERIALS DATA (AGGREGATE B)

AGGREGATE DATA
1/2" MAXIMUM MEDIUM TYPE B

Sieve	% Passing	Specification Tolerance
3/4	100	100
1/2	95	95 - 100
3/8	85	80 - 95
4	64	54 - 71
8	47	38 - 54
16	33	
30	23	17 - 32
50	14	
100	7	
200	3	3 - 8

Kc[1] = 1.5

Kf[1] = 1.3

Km[1] = 1.3

Specific Gravity$_c$ = 2.78

Specific Gravity$_f$ = 2.59

Specific Gravity$_{avg.}$ = 2.71

Sand Equivalent Value[2] = 84

DESIGN SET

	A	B	C	D
Bitumen Ratio (%)	6.6	7.1	7.4	7.6
Stability	41	41	37	37
Sp. Gr.	2.22	2.23	2.25	2.28
Voids (%)	9.2	8.4	6.8	5.5
Cohesion	456	420	420	595
Flushing	None	Slight	Slight	Moderate

O.B.C. = 7.1 - 7.4%

Notes:
1. Specification Requirement - 1.7 maximum
2. Specification Requirement - 45 minimum

TABLE 3

PRODUCT EVALUATION TEST
DATA SUMMARY (AGGREGATE B[1])

ADDITIVE	OPTIMUM BITUMEN CONTENT (%)	M_r (psi x 105)	STABILITY	SPECIFIC GRAVITY	VOIDS (%)	COHESION	SURFACE ABRASION LOSS (gm)
Control (Conv. Mix)	7.4	4.91	37	2.25	6.8	130	33.5
Ramflex (1.0%)[2] Crumb Rubber	8.2	3.34	23	2.28	4.6	335	27.5
BoniFibers (0.25%)	7.9	1.10	39	2.27	5.5	275	29.2
FiberPave 3010 (0.3%)	7.9	0.94	34	2.23	7.0	235	27.6
Marvess Olefin (0.4%) (60 Den)	7.9	6.50	35	2.25	6.3	230	23.8
Marvess Olefin (0.4%) (16 Den)	7.9	3.50	39	2.20	8.3	142	25.0
G-274 (1.0%) Crumb Rubber	8.2	2.91	23	2.24	6.2	212	34.5
ARS (Arm-R-Shield)	8.2[3]	0.95	30	2.18	8.7	141	8.1
PlusRide	8.5	2.57	2	2.22	3.1	56	12.5

Notes:
1. 1/2" maximum medium Type B.
2. All percentages are by dry weight of aggregate.
3. This mix used a binder which contained 76% asphalt, 20% rubber, and 4% extender oil. Considering asphalt only, it was 6.2% by dry weight of aggregate.

With respect to asphalt content, the ARS mix behaved differently from the other rubber products. The ARS mix actually utilized <u>less</u> asphalt, only 6.2%. Some of the finer rubber particles used in the binder apparently went into solution (as claimed by the manufacturer), thereby acting as an asphalt extender.

2. Hveem Stability (California Test 366)

Although none of the fibers had a noticeable effect on stability, the rubber additives did lower the stability in varying degrees. The PlusRide rubber mix exhibited the highest reduction in stability (stability dropped to a value of 2) and the ARS rubber mix showed the least reduction in stability for the rubber mixes (stability dropped to a value of 30). However, due to the resilient nature of the rubber mixes, permanent deformation does not seem to be occurring and, thus, this test for stability may not be a true indicator of field performance.

3. Surface Abrasion (California Test 360, Method B)

Surface abrasion was improved in all cases except that involving the use of the G-274 crumb rubber which showed no improvement. The biggest improvement was seen in the ARS and PlusRide mixes with losses of only 8.1 and 12.5 grams, respectively. This is a dramatic improvement from the 33.5 gram loss of the control mix. The other rubber and fiber mixes showed losses ranging from 23.8 to 29.2 grams.

4. Specific Gravity (California Test 308)

Specific gravity, which is largely a function of air voids, did not vary significantly from the control mix which was 2.25 (with 6.8% voids). In all miles except the PlusRide, as the voids went up or down, the specific gravity went down or up, respectively. The ARS exhibited the highest voids, 8.7%, and lowest specific gravity, 2.18. This could have been due to poor compaction during specimen fabrication. The PlusRide mix had a 2.22 specific gravity with a very low void content of 3.1%. The lower specific gravity is explainable by the high rubber content (3% by weight of total mix) and the large size of some of the rubber particles (1/4-inch maximum). This mix should be very impermeable.

5. Cohesion (California Test 306)

The cohesion (or tensile strength) improved in all mixes except the PlusRide. The control mix exhibited a value of 130 whereas the modified mixes ranged from 141 for the ARS mix to 335 for the Ramflex mix. The higher cohesion values are expected when using fiber or rubber additives so the low PlusRide value was very puzzling. This could possibly be due to the gap grading and/or to poor bonding of the large (1/4") rubber particles in the mix.

6. Resilient Modulus (M_r) (Chevron Method)

Because Caltrans does not have a formalized M_r test method, resilient modulus values are shown for informational purposes only and will not be discussed in this study.

E. Summary of Evaluation Testing

Looking at Tables 1 and 3 for the testing conducted using aggregate from sources A and B, respectively, it can be concluded that the fibers and rubber generally behaved similarly (even though some of the individual results varied, considering OBC and surface abrasion loss only). The partial results in Table 1 and the complete results in Table 3 indicate that the addition of certain fiber or rubber additives to an AC mix could provide better resistance to surface abrasion.

Except for PlusRide, all the mixes looked good with respect to Caltrans mix design criteria. The "optimum" PlusRide mix had a high asphalt content, very low Hveem stability, low voids, and very low cohesion. The high asphalt content and low voids are normally considered a very high risk for bleeding in the field. This, coupled with very low laboratory stability, suggests a high risk of instability in the field. It is alarming to have this many factors that would normally be considered problem areas in a conventional AC mix. But, according to the manufacturer, the design parameters do not apply to the PlusRide mix. It is too early to test the validity of this statement, considering Caltrans has only one field installation using this product(2).

VII. FIELD INSTALLATION

After the lab testing was almost completed, a field installation was placed using several of the fiber mixes and one rubber mix. Based on the laboratory test results and other factors (egs. economics, product availability, project size, products already used in other field test sections, design conditions, etc.) three fibers, (BoniFibers Type B, Hercules Fiber Pave 3010 and Phillips Marvess Olefin), and one rubber (Ramflex), were selected to be placed in field test sections, along with a control section of conventional mix.

The project selected for the field installations of the modified AC mixes was in a mountainous snow region on Interstate 80 near Floristan, California (03-NEV-80, P.M. 23.5 to 28.0, Contract No. 03-275014).

The contractor for the project was Granite Construction Co., Sacramento California, and state personnel were John Leonhardt, Resident Engineer, Rick Liptak, Street Inspector, Doug Jones, Materials Inspector, and Guy Buckman, Plant Inspector.

The existing pavement was PCC which was badly cracked and exhibited severe surface abrasion. For the majority of the project, Ramflex rubber was used, but the experimental field installations were all placed end-to-end in the heavily traveled westbound truck lane (Figure 2). The AADT for the roadway is about 18,000 with 12% trucks (T.I. of about 10.5).

A. Preliminary Investigation of Site

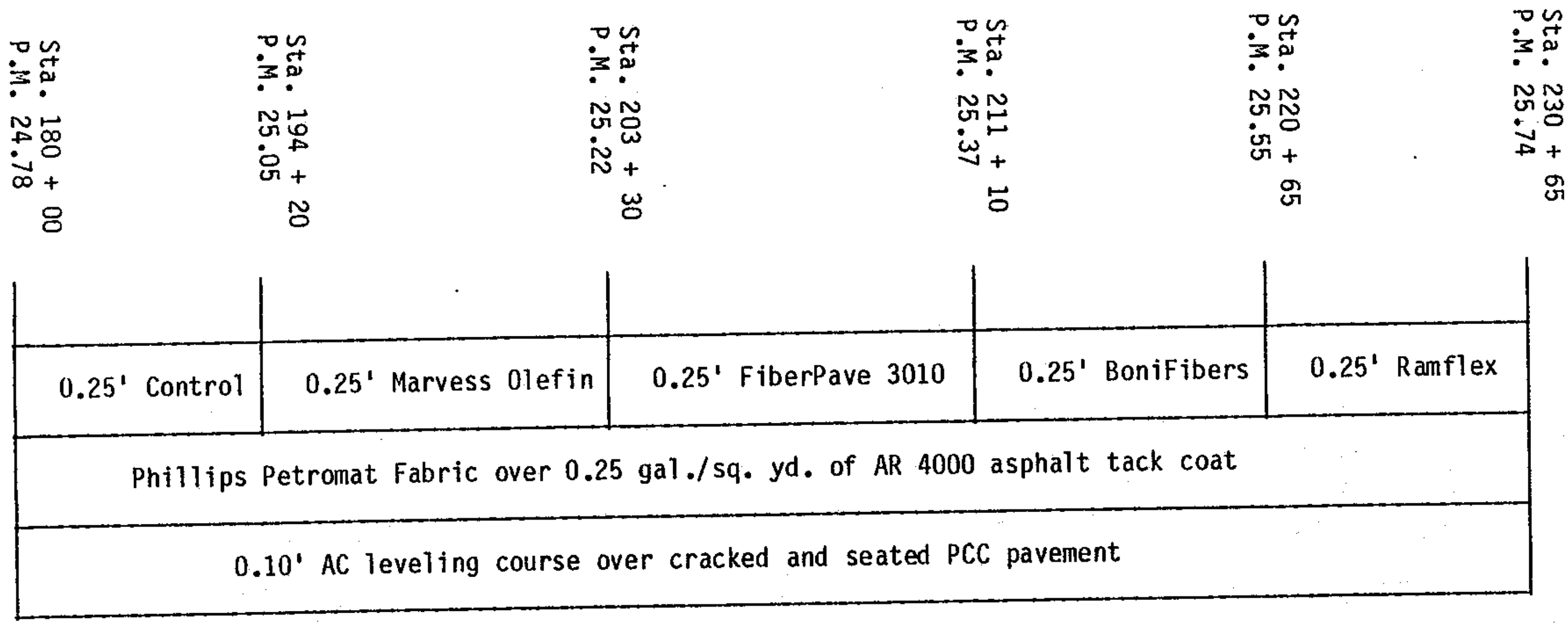
Figures 3 and 4 show the existing pavement condition. The PCC pavement contained longitudinal and transverse cracking up to two inches wide at some locations. Some cracks had been filled with crack sealer and there were some spalled areas at joints or cracks as large as one foot by two feet.

B. Mix Design Work

After the project was selected, mix designs had to be completed for each additive using the aggregate and asphalt chosen for the project. The aggregate chosen was different from that used in the initial lab research and quite different test results were obtained. The aggregate came from Granite's Patrick-Sparks Pit located near Sparks, Nevada. Data on the aggregate are shown in Table 4. A summary of the design work for the project is shown in Table 5. All mixtures (fiber, rubber and control) utilized a 3/4-inch maximum, medium, Type A aggregate gradation with Chevron AR-4000 asphalt (same asphalt used in lab research).

In the mix design testing, using the project aggregate and asphalt, the surface abrasion loss was <u>not</u> reduced by the addition of rubber or fibers. However, the placement of these products was still recommended so that their performance could be evaluated in an actual field installation.

A very important item revealed in the mix design lab testing was the temperature required for mixing and compacting the Ramflex crumb rubber mixtures. When the very high surface abrasion loss was obtained at the



Notes: 1. All mixes used 3/4" Type "A" maximum medium grading.

2. All 5 test sections were placed in 2 lifts with the final lift being 0.15' thick.

FIGURE 2, TEST SECTION LAYOUT
(Westbound Truck Lane)

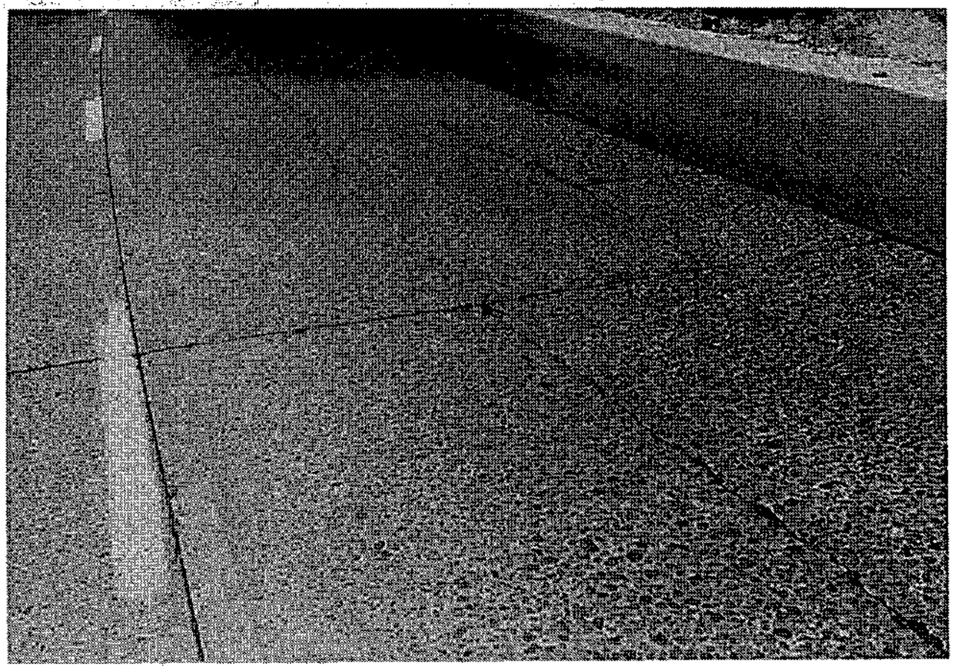


Figure 3
Existing Condition of Roadway

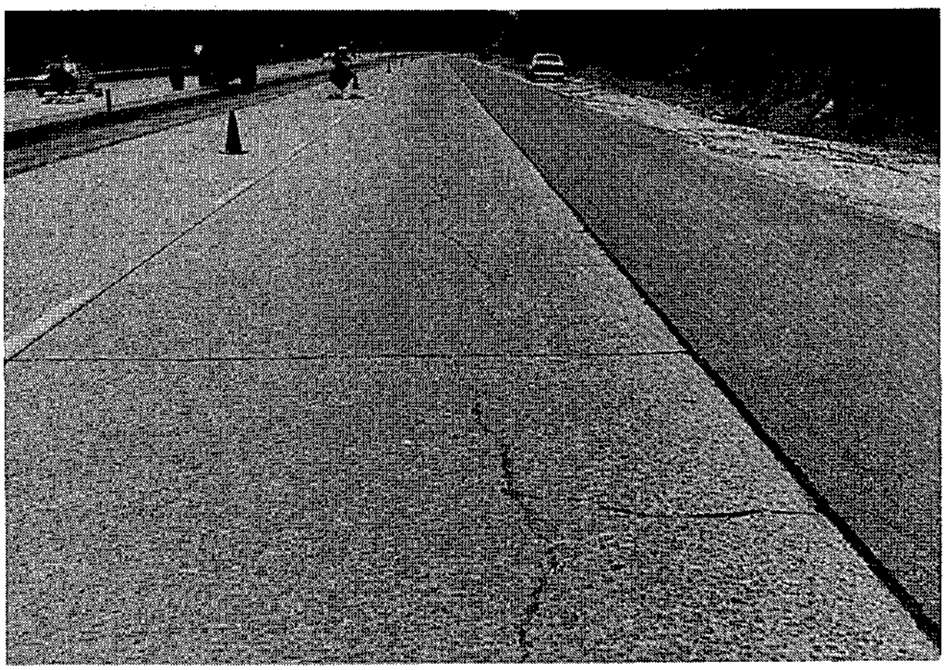


Figure 4
Existing Condition of Roadway

TABLE 4

MATERIALS DATA (PATRICK-SPARKS)

3/4" MAXIMUM MEDIUM TYPE A			
Sieve	% Passing	Specification Tolerance	
			Kc^1 = 1.4
			Kf^1 = 1.2
1	100	100	
3/4	96	95 - 100	Km^1 = 1.3
1/2	84		
3/8	71	65 - 80	
4	54	44 - 59	$\text{Specific Gravity}_c$ = 2.50
8	39	31 - 45	
16	28		$\text{Specific Gravity}_f$ = 2.68
30	19	13 - 26	
50	12		$\text{Specific Gravity}_{avg.}$ = 2.59
100	7		
200	4	3 - 8	Sand Equivalent Value^2 = 65

Notes: 1. Specification Requirement - 1.7 maximum

2. Specification Requirement - 45 minimum

normal 230°F fabrication temperature, it was decided to try higher temperatures to possibly obtain better compaction. Referring to Table 5, at the higher fabrication temperatures, the stability values increased and the surface abrasion loss decreased dramatically. However, the Ramflex mix still didn't show any improvement compared to the conventional mix. It was eventually recommended that a 300± 10°F breakdown rolling temperature for the Ramflex rubber mix be used on the project.

C. Plant Operations

1. The Plant

Two plants were used on the project. All conventional mix, which was used in the leveling course, all shoulders, and the median, was produced in the Granite Patrick <u>drum</u> plant located near Sparks, Nevada. Since the fiber and rubber additives required a <u>batch</u> plant for production, another plant, the Granite Sparks batch plant, was used to produce these mixes and the control mix. For the purpose of this report only its operation will be discussed.

The batch plant is located in Sparks, Nevada, about 20 miles east of the project. It is a 6,000 lb capacity plant manufactured by Barber Green (Figure 5), and the operation was automatic except for the manual control of the drier burner and the manual addition of the rubber and fibers. They were added into each batch via a specially installed 12-inch by 30-inch steel chute located directly over the mixer paddles of the pug mill (Figure 6).

The additives were ordered in specified bag weights in order to be compatible with 6000 lb batches.

TABLE 5

MIX DESIGN TEST DATA FOR
03-NEV-80 TEST SECTIONS

ADDITIVE	% USED	OPTIMUM BITUMEN* CONTENT (%)	STABILITY	SPECIFIC GRAVITY	VOIDS (%)	SURFACE ABRASION LOSS (gm)	TEMP.(°F) MIX/COMPACT
Control (Conv.Mix)	-	7.1	38	2.26	3.3	28.9	**
Ramflex	1.0	7.6	37	2.23	3.9	28.8	350/300
Ramflex	1.0	7.6	35	2.21	4.7	50.3	350/230
Ramflex	1.0	7.6	33	2.22	4.3	59.2	**
BoniFibers	0.3	7.3	40	2.19	6.0	35.8	**
Fiber Pave 3010	0.3	7.3	34	2.18	6.4	40.4	**
Marvess Olefin	0.3	7.3	34	2.22	5.6	41.8	**

Notes: * TransLab recommended O.B.C. (California Test 367) using AR-4000. (The O.B.C. for the control sample, although exhibiting less than 4.0% voids, was selected due to the high void content (6.4%) at 6.8% asphalt content. The possibility of high permeability and the freeze/thaw action anticipated in the placement area justified compromising a design criterion to obtain a "tighter" mixture).

** Normal mixing (300°F) and compacting (230°F) temperature (California Test 304 & 360, Method B).

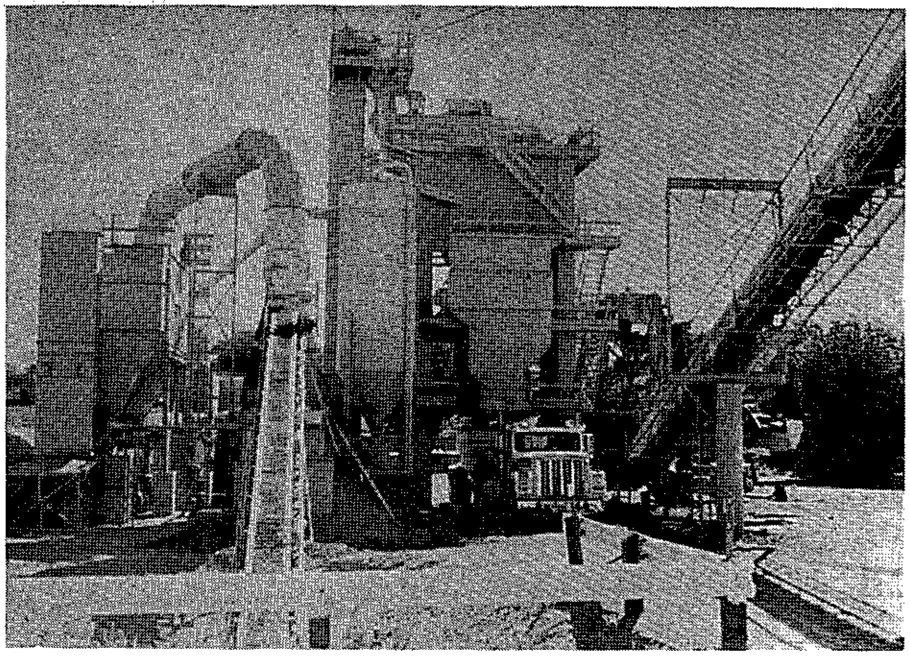


Figure 5
6000 lb Batch Plant

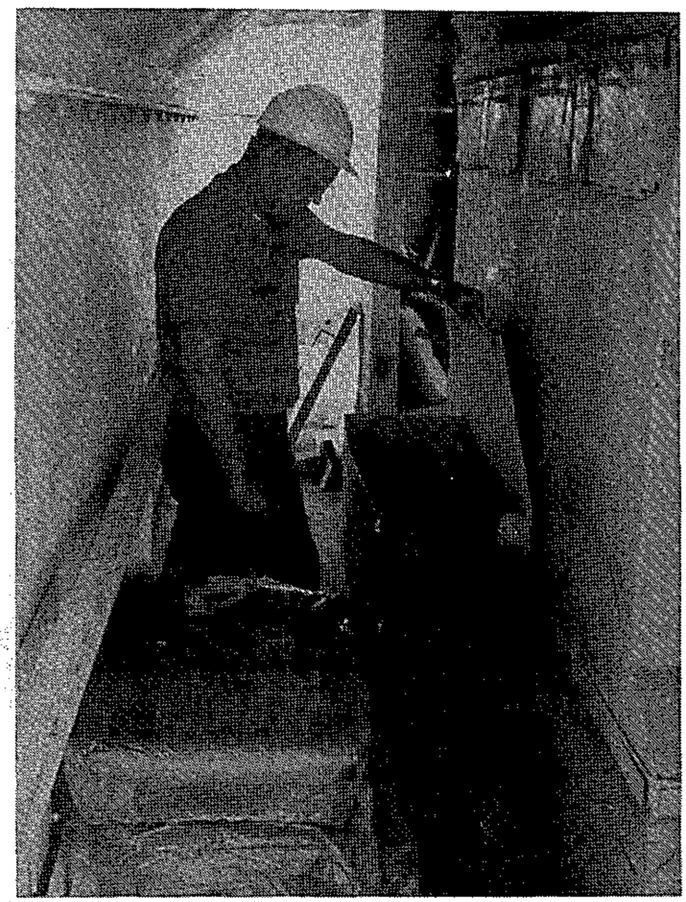


Figure 6
Special Chute Above Pugmill
(Bags of Ramflex are
in foreground)

2. Typical Batching Procedure

The packaged (bag) weights for each additive were as follows:

- Ramflex Rubber - 56.5 lb - one bag per batch
- BoniFibers - 8.5 lb - two bags per batch
- Hercules Fibers - 17 lb - one bag per batch
- Phillips Fibers - 18 lb - one bag per batch.

These weights provided the required 1.0% rubber and 0.3% (approx.) fibers (by dry weight of aggregate) for each 6000 lb batch produced.

The typical batching procedure for the modified mixes was as follows:

a. Hot dry aggregate dropped from the weigh box into the pugmill.

b. Rubber or fiber added to pugmill via special chute.

c. 20 second "dry" mix cycle.

d. Asphalt binder added.

e. 30 second "wet" mix cycle.

f. Completed modified mix dropped from pugmill into truck.

The Ramflex and BoniFibers were added directly, via the chute, in their bags, which were polyethylene and melted (200°F melting point) upon contacting the hot aggregate. However, the Hercules and Phillips Fibers were packaged in polypropylene bags (320°F melting point) which had to be cut and the fibers dumped from the bags into the chute. This required excessive handling.

The amount of asphalt actually used in the various modified mixes was that recommended from the mix design work.

3. Problems Encountered

One serious problem occurred during the first day of fiber batching. There was a mix-up in the batching temperature instructions and some of the polypropylene fibers were melted due to excessive temperature. This problem could possibly have been associated with a malfunction of the manual drier burner.

The initial truck loads on the first day of paving contained rubber mix batched between 300 and 350°F. Later, when the fiber mixes were eventually batched, they mistakenly were produced at temperatures above 320°F. This did not create any problems with the BoniFibers, a polyester fiber with a melting point of about 480°F. However, the Hercules and Phillips fibers, being polypropylene and having a softening point around 300°F and a melting point of about 320°F, were completely melted in almost all loads delivered to the street. Subsequently, proper instructions were given to the plant so the batch temperatures would be correct for the final lift of fiber mixes placed 12 days later. Even though this was done, a few batches (at least one batch of each fiber) in the final lift were produced at temperatures above 300°F due to difficulty in maintaining burner temperature manually. It was quite possible the polyproplyene fibers were softened or even melted in these batches; however, this was not apparent at the street.

Another problem was the dry mix cycle required for the modified mixes. This caused a costly slow-down in the production of these mixes. Each batch that was mixed required a longer total mix time (50 seconds compared to 30 seconds) and, as a result, the production rate of all modified mixes was reduced due to the 67% increase in mixing time. Therefore, all aspects of the project (trucks, paving crew, etc.) were slowed due to this reduction.

D. Street Operations

1. General Pavement Preparation

The existing PCC pavement was first cracked-and-seated into approximately four-foot by six-foot segments and then a 0.1-foot leveling course was placed using conventional AC. A tack coat of AR-4000 was then applied at a rate of 0.25 gallon per square yard followed by Phillips Petromat, a paving fabric. The fabric extended one foot into the shoulder area and, for the most part, the tack coat did not bleed through the fabric prior to placing the mix (Figure 7). The modified mixes were then placed over the fabric in two lifts, the first being 0.10 foot and the final lift being 0.15 foot thick.

2. Equipment Used

The rubber and fiber mixes were transported from the plant to the street using bottom dump trucks. The paving equipment consisted of a rubber tire Blaw Knox paver (B-180) with a KoCal pickup machine (Figure 8), followed by two Hyster 10-ton static steel-wheel tandem rollers for breakdown and finish rolling.

3. Placement of Mixes

All the test sections were placed in the westbound truck lane only (12 feet wide).

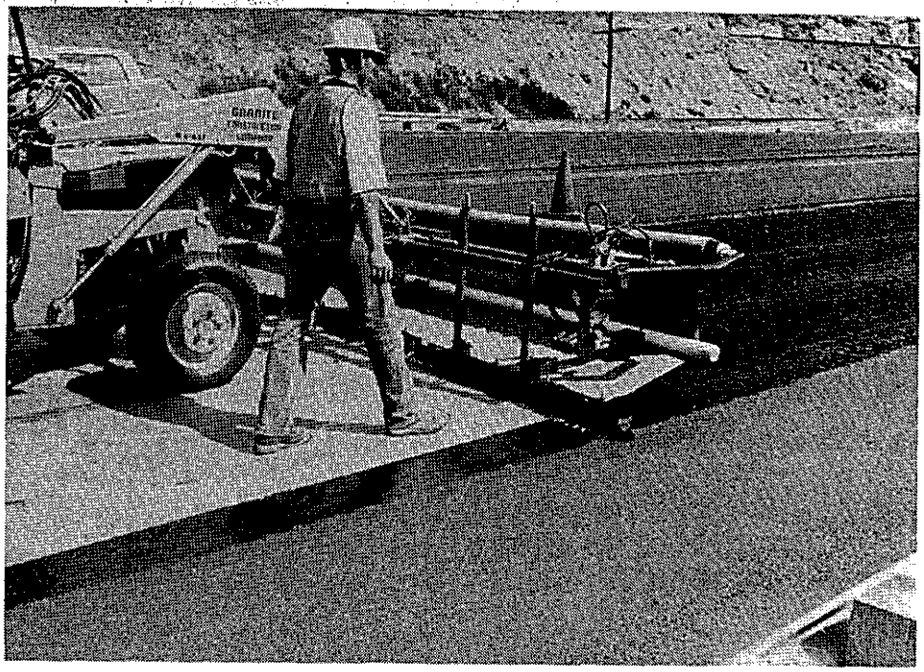


Figure 7
Fabric Placed Prior to Overlay

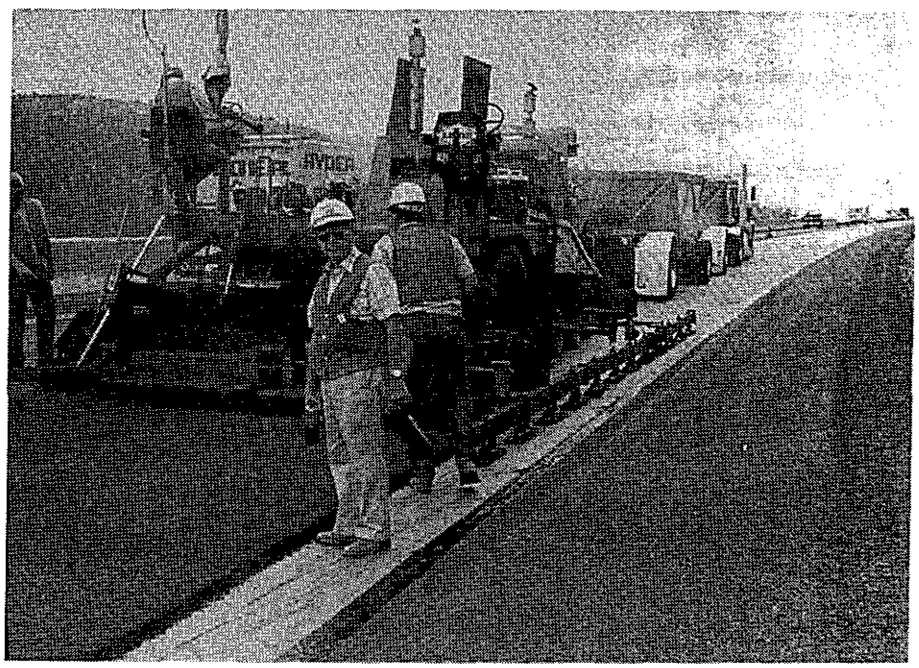


Figure 8
Blaw Knox Paver with KoCal Pickup Machine

Initially, it was planned to place 1000-foot test sections of each modified mix and the control, but when the fiber mixes were batched, the material did not cover 1000 feet. Also, one truckload of Hercules fiber mix was rejected due to inadequate mixing of the fibers. This resulted in the following lengths for each test section (See Figure 2):

Ramflex Crumb Rubber	1000 feet
BoniFibers	955 feet
Fiber Pave 3010 Fibers	780 feet
Marvess Olefin Fibers	910 feet
Control	1420 feet

The designated Ramflex rubber test section was the last 1000 foot prior to starting the fiber sections (Ramflex was placed on the balance of the project).

On September 5, 1984 the first lift of the test sections was placed (0.10 foot thick). The ambient temperature ranged from about 60 to 75°F. There was a slight breeze and it was cloudy. Although the weather was generally unsettled with occasional sprinkles, only one delay occurred (for about an hour) due to rain.

One minor problem that occurred was the waiting time between the different mixes. As each different product was mixed, the trucks waited until all of that particular material was mixed and in the trucks, then they would deliver it in convoy to the street. This was done to prevent mix-ups and to allow for continuity in each test section. There were four truck loads per test section and six for the control section.

The first mix placed in the morning was the one containing Ramflex rubber. No problems were encountered in placement or rolling. The mix temperatures ranged from about 300 to 330°F during breakdown rolling.

When the plant switched to the fiber mixes, the mix-up in batching information caused the mixes to be batched at the same high temperatures as the Ramflex. As stated earlier, this did not create a problem with the BoniFibers, but the Hercules and Phillips Fibers were melted. It was hoped that this would not cause problems later because it would be overlaid with a final 0.15 foot lift. The BoniFibers created no problems during placement and rolling, but did appear to create a minor problem with the KoCal pickup machine. The fibers were observed accumulating on, and hanging from, the flights (Figure 9). The paving foreman commented that on a long project, it may be necessary to resort to end-dump trucks to avoid the problem of balls or gobs of fibers dropping into the mix from the flights of the pick-up machine. Another noticeable difference with the BoniFiber mix was the brown, dry appearance after rolling (Figure 10). Close inspection showed tiny asphalt-stained fibers protruding from the mix and giving the pavement the brown appearance.

The other fiber mixes appeared black, but this was probably due to the fibers being melted. There was no trace of fibers on the pickup machine and these mixes exhibited tenderness during rolling, leaving roller lines in the mix (Figure 11). With additional rolling, after the pavement cooled, these lines mostly disappeared.

On September 17, 1984, the final 0.15 foot lift of the test sections was placed. The ambient temperature was about 65°F. It was overcast and breezy, but no rain fell during placement of these final test section lifts. The first material placed was the Ramflex rubber mix and again no problems were encountered. The mix temperature in the windrow was 300 to 310°F and the mix was rolled at approximately 300°F. The finished mat looked very good (Figure 12). After placing this rubber mix, the hot bins at the plant were emptied and the aggregate temperature was reduced to accomodate the 290°F mix temperature for the polypropylene fibers.

The BoniFiber mix (polyester fiber) was the first fiber mix placed and the temperature in the windrow ranged from 260 to 300°F. The mix looked very similar to the first lift placed, i.e., brown in color (Figure 13).

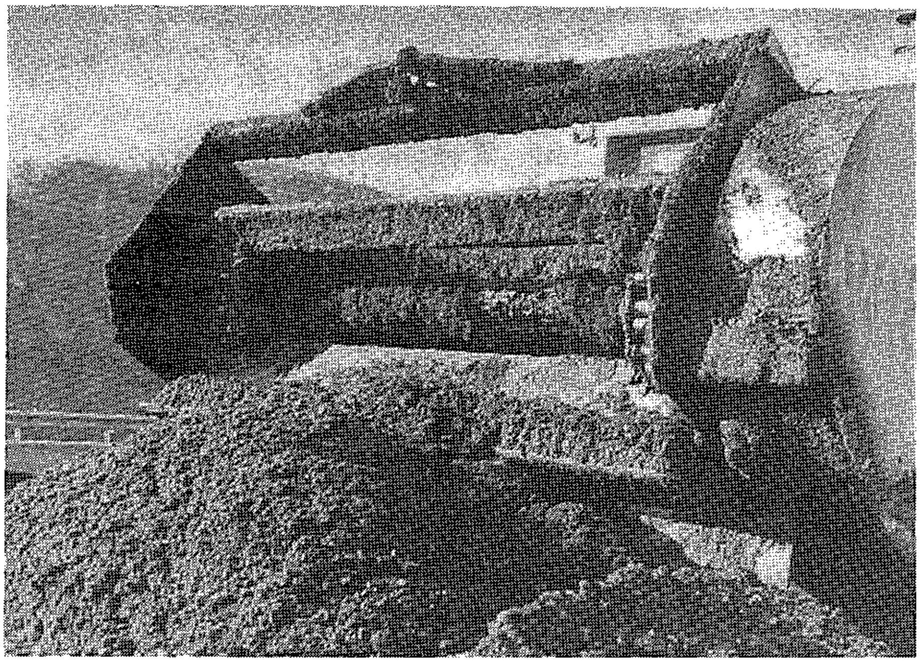


Figure 9
Fibers Accumulating on Flights of Pickup Machine

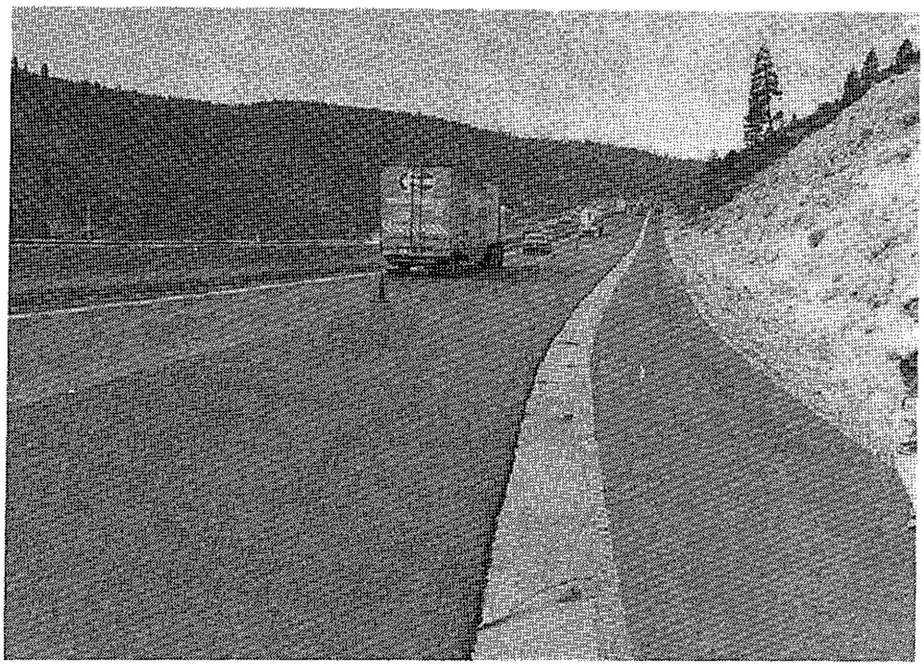


Figure 10
Finished Appearance of BoniFiber Mix - First Lift

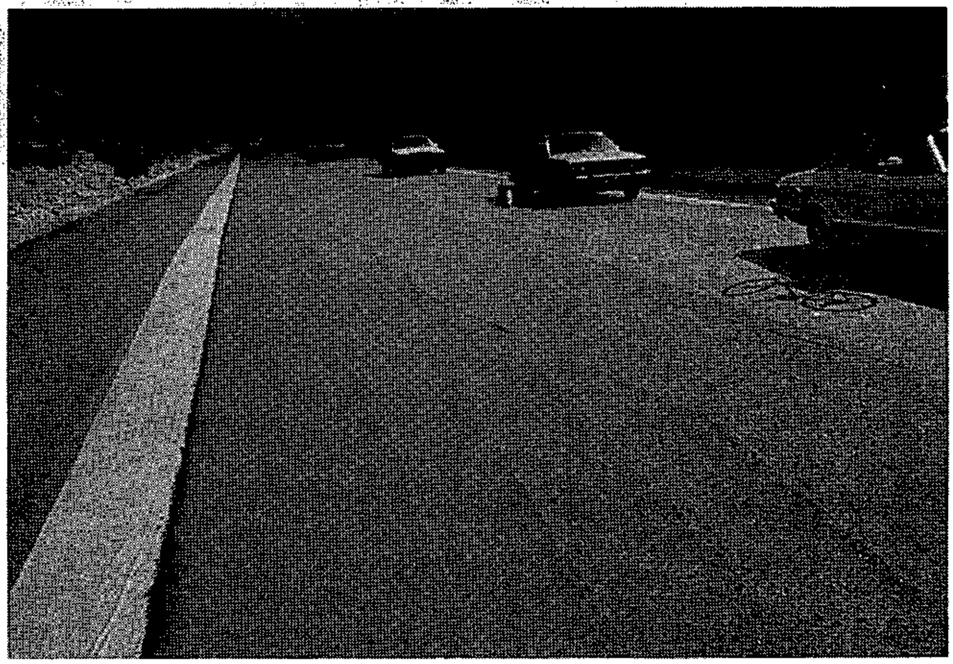


Figure 11
Tenderness Problems in Marvess Olefin Mix - First Lift

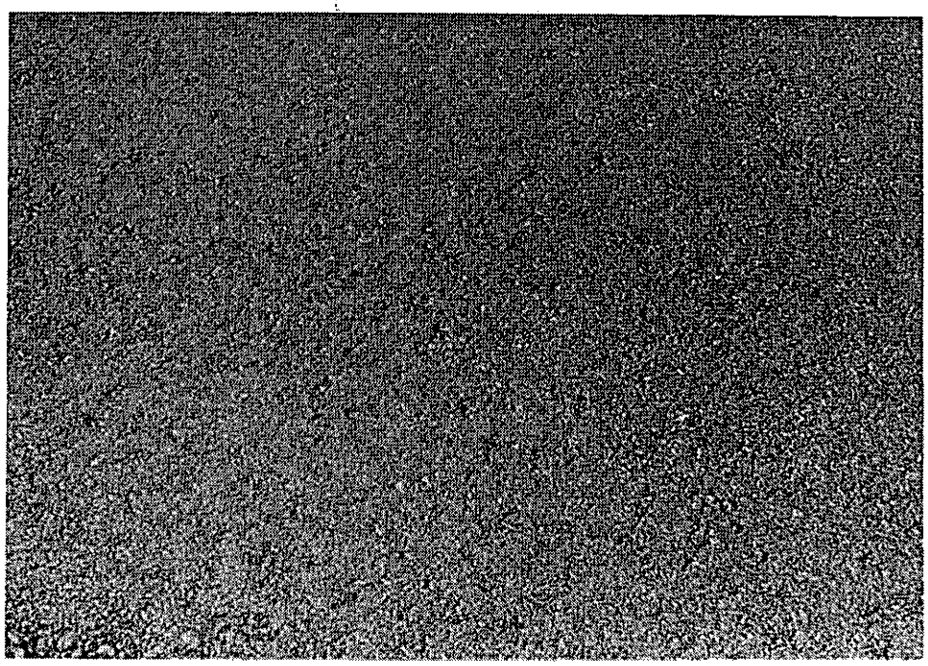


Figure 12
Ramflex Crumb Rubber Mix - Final Lift

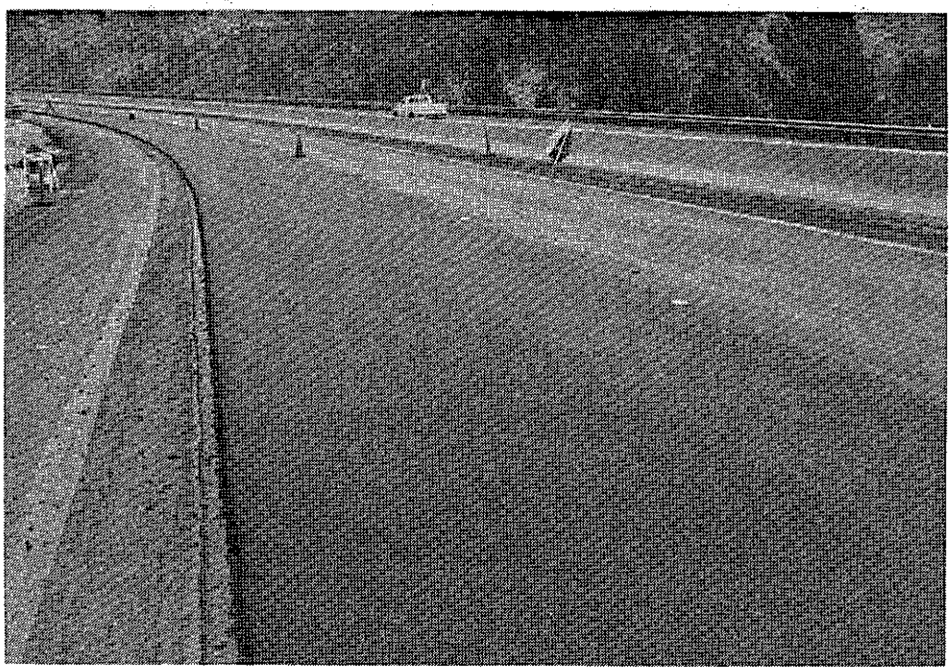


Figure 13
BoniFiber Mix - Final Lift

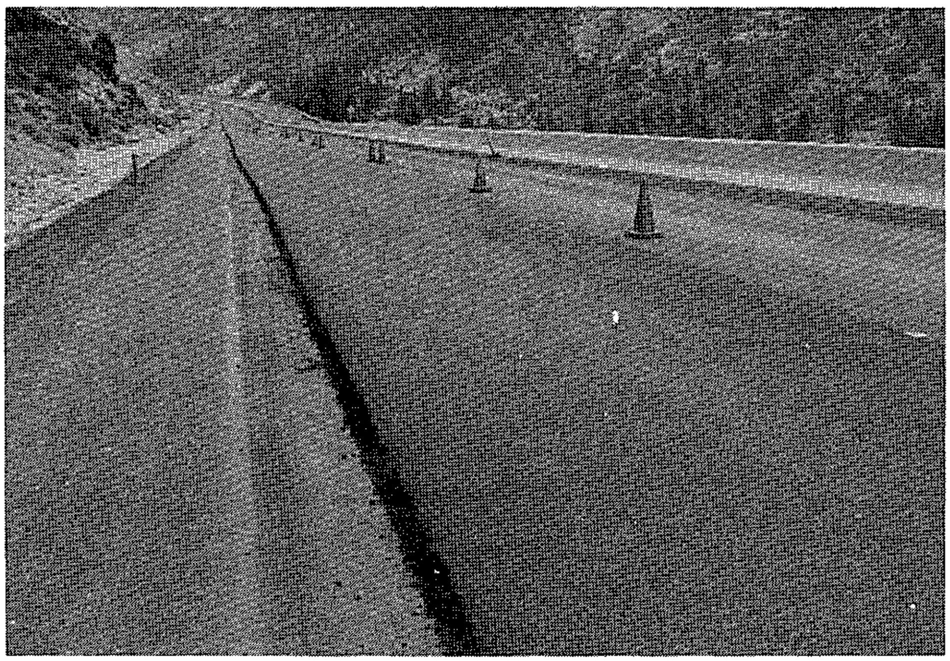


Figure 14
Fiber Pave 3010 Mix - Final Lift

Other than the fibers again clinging to the pickup machine, no problems were encountered and the mix looked very good.

The Hercules and Phillips fiber mixes (polypropylene fiber) were placed with little problem as compared to the first lift. The fibers were quite evident in the mix and they clung to the KoCal pickup flights as had the BoniFibers. The temperature in the windrow ranged from 250 to 290°F. Both the mixes rolled very well this time with no tenderness evident. Breakdown rolling for all fiber mixes was accomplished at about 260 to 270°F. The only problem encountered was with the Phillips fiber. The first two truck loads which arrived at the street (windrow temperature 250°F) contained some uncoated aggregate and fibers. These loads were apparently not mixed adequately at the plant. This did not appear to be a major problem and was probably due to the low mix temperature. These two fiber mixes also appeared discolored, and were reddish brown in color. The finished mat looked very good for these two fiber mixes (Figures 14 and 15).

The control mix was the last mix placed in the experimental section area. It was placed and rolled with no problems other than one load of mix having a windrow temperature of 350°F, which is excessive. The other windrow temperatures ranged from 300 to 325°F. The finished mat looked very good (Figure 16).

E. Lab Testing of Street Samples

All mixes (first and final lifts) were sampled from the street and lab tests were conducted. One large sample (about 80 lb) was obtained from each lift from each test section. Material was taken from various locations in the windrow to obtain a representative sample. All testing was conducted using companion samples (except surface abrasion, where 3 samples were used). A summary of mix test results is shown in Table 6. Additional data, including gradings and Abson recovery results, are located in Appendix D. It appears that the additives had some effect on the asphalt, as shown by the viscosity

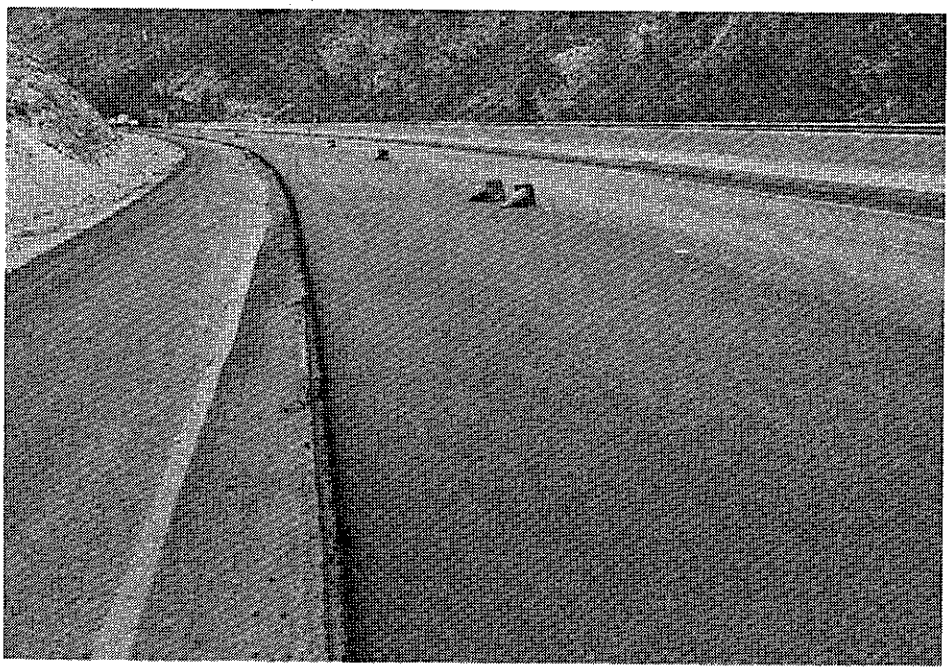


Figure 15
Marvess Olefin Mix - Final Lift

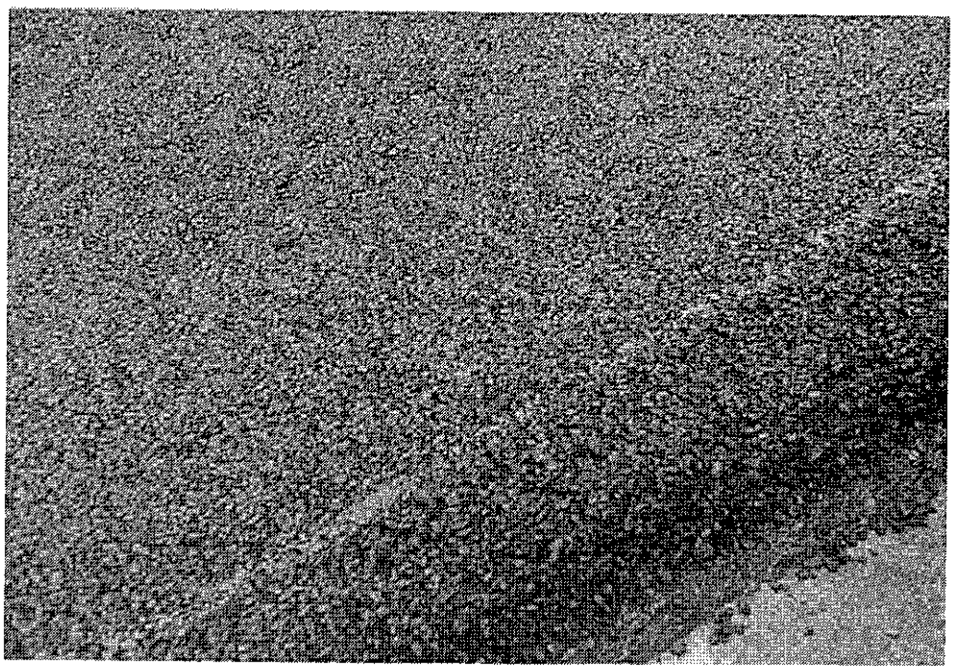


Figure 16
Control Mix (Conventional AC) - Final Lift

tests in the results of the recovered asphalt. This, in turn, probably affected the characteristics of the modified mixes, but it is uncertain to what degree.

It should be pointed out that the original design did not incorporate bag house dust into the gradation. But at the plant it was decided that bag house dust would be used (up to 3%) and this probably affected the mixes to some degree. The test results from the control mix (final lift only) indicate that the extra-fine bag house dust (very high surface area) probably acted as an extender and created an unstable mix. The control mix was out of specification on the passing No. 200 fraction (9.4% where the specification permitted only 3 to 8%). Some of the other mixes were also out of specification on the passing No. 200 fraction (See Appendix D), but not quite as high as the control mix (except for the Ramflex mix in the first lift). It is felt that these fines will have a negative effect on mix characteristics, so it would be unfair to compare the mixes between the first and final lift. The data from the final lift is, therefore, presented for information only.

Looking at the data from the <u>first lift only</u>, it is quite evident that all additives improved the resistance to surface abrasion (even though the Phillips and Hercules fibers were melted). It is interesting to note that the fiber and rubber mixes showed a significant improvement over the earlier project design samples. The asphalt content for the control mix was about 0.5% lower than the design value, while for the Marvess Olefin mix, it was a little higher. However, they were still within Caltrans' tolerance of $\pm$0.5%. Due to previous experience,(1)(2) the test results for asphalt content determination cannot be considered valid in all cases (due to melted fibers or rubber plugging the extraction filters). Therefore, asphalt content will not be discussed in detail for these mixes.

F. Nuclear Gauge Density Tests

In situ density tests were conducted on all mixes in the field using the Campbell Model B(R) Mark II nuclear density gage. The mixes that were placed in the field did not properly represent the ones fabricated in the lab during design (use of bag house dust and high passing No. 200 fraction - see Section E), so new target densities were obtained from the field mixes (see Table 6). The relative compaction was, therefore, based on these new target densities. The density data are shown in Table 7. The tests were conducted on the final lift four days after placement. All mixes, including the control mix, had at least 93% relative compaction with the Ramflex rubber mix indicating the highest value of 97%.

G. Coring of Test Sections

About six weeks after placement of the final lift, the test sections and the control section were cored. Four-inch cores were obtained and laboratory tests were conducted.

1. Coring Locations

Table 8 provides information on the location of the cores.

2. Lab Testing of Cores

Laboratory tests were conducted on all cores and the results are presented in Tables 9 and 10. Each core was examined closely to determine the thickness of each lift and then the lifts were separated by saw cutting. Each lift was then tested and the test results presented in separate tables.

Based on Table 9 data, the following comments can be made concerning the final lift:

- Lift thickness: The average thickness was about 0.16 ft with a range of 0.15 to 0.17 ft. This shows good paving control.

- Asphalt Content: It appears that the asphalt content was low in all mixes except the Marvess Olefin fiber mix. As mentioned earlier

TABLE 6

STREET SAMPLE TEST DATA

ADDITIVE		SAMPLE NO.	ASPHALT CONTENT (%)[3,4]	STABILITY	SPECIFIC GRAVITY	VOIDS (%)	COHESION	SURFACE ABRASION LOSS (gm)
First Lift	Control (Conv.Mix)	842-192	6.6	40	2.26	4.6	534	28.3
	Ramflex	842-190	7.4[1]	14	2.25	3.0	331	23.1[2]
	BoniFibers	842-193	7.3	38	2.19	6.8	342	26.8
	FiberPave 3010[5]	842-195	7.3[5]	30	2.22	5.5	463	24.1
	Marvess Olefin[5]	842-194	7.7[5]	30	2.23	4.7	450	20.5
Final Lift	Control (Conv.Mix)	842-204	7.4	13	2.30	1.7	440	24.9
	Ramflex	842-208	8.2	10	2.25	2.2	287	21.4
	BoniFibers	842-207	7.3	34	2.21	6.0	389	31.8
	Fiber Pave 3010	842-206	7.1	28	2.23	5.1	400	32.6
	Marvess Olefin	842-205	7.0	30	2.24	5.1	495	24.0

Notes:
1. Difficulty flushing out after extraction.
2. Fabricated @ 300°F.
3. Hot extractor (California Test 310) was used for all first lift mixes.
4. Vacuum extractor (California Test 362) was used for all final lift mixes.
5. No fibers visible in mix (in all other modified mixes the rubber or fibers were visible after extraction).
6. All numbers represent an average of two samples except for the surface abrasion (three samples).
7. California test methods were used for all tests.

TABLE 7

NUCLEAR GAUGE DENSITY DATA

ADDITIVE	DENSITY[1] (pcf)	RELATIVE COMPACTION[2] (%)
Control (Conv. Mix.)	134.0	93
Ramflex	136.4	97
BoniFibers	127.8	93
Fiber Pave 3010	129.3	93
Marvess Olefin	132.9	93

Notes: 1. Average of 4-9 tests per test section.
2. Based on lab maximum densities from street samples.

TABLE 8

CORE LOCATIONS

Test Section	Core Number	Station	Post Mile
Ramflex	1	233+65	25.61
	2	222+65	25.59
	3	221+65	25.57
BoniFibers	4, 4A, 4B	219+65	25.53
	5	216+65	25.47
	6	212+09	25.39
Fiber Pave 3010	7	210+09	25.35
	8	207+09	25.29
	9	204+32	25.24
Maryess Olefin	10	202+32	25.20
	11	199+32	25.15
	12	195+18	25.07
Control (Conv. Mix.)	13	193+18	25.03
	14	192+18	25.01
	15	191+18	24.99

Note: Cores were taken 2-3 feet from outside edge of the traveled way.

TABLE 9

CORE TEST DATA (FINAL LIFT)

SAMPLE NO.	TEST SECTION	CORE NO.	LIFT THICKNESS (FT.)	TOTAL ASPH. EXT. (%)	GRADING (% PASSING) 1"	3/4"	1/2"	3/8"	#4	#8	#16	#30	#50	#100	#200	SP. GR.	REL. COMP. (%)
842-250	RAMFLEX	1	0.16	7.2		100	87	70	49	38	30	23	17	13	9.6	2.22	99
"	"	2	0.16	6.8	100	96	81	62	46	36	28	22	17	13	9.5	2.26	100
"	"	3	0.17	6.7		100	89	72	50	38	29	22	17	12	9.1	2.28	101
842-251	BONI FIBERS	4	0.17	6.6		100	92	78	53	40	31	24	17	11	7.9	2.10	95
"	"	4A	0.16	6.7		100	95	81	55	41	33	25	18	12	9.1	2.10	95
"	"	5	0.16	7.0		100	89	73	53	38	29	23	17	12	8.6	2.19	99
"	"	6	0.18	7.0	100	98	91	81	57	41	31	24	17	12	9.1	2.11	95
842-252	FIBER PAVE 3010	7	0.16	7.2	100	99	90	79	56	40	32	25	18	12	8.3	2.19	98
"	"	8	0.17	7.0		100	82	77	56	40	30	24	17	12	8.4	2.14	96
"	"	9	0.16	6.3		100	88	72	53	38	29	22	17	11	8.5	2.13	96
842-253	MARVESS OLEFIN	10	0.16	6.4	100	98	92	74	49	37	30	24	18	12	9.4	2.14	96
"	"	11	0.16	7.8	100	98	91	79	51	38	30	23	17	12	8.5	2.18	97
"	"	12	0.16	7.4		100	89	79	57	42	33	25	18	13	9.3	2.19	98
842-254	CONTROL	13	0.16	6.0		100	91	74	48	36	29	23	17	12	9.0	2.22	96
"	"	14	0.15	7.2		100	94	78	51	37	30	24	18	12	9.0	2.24	97
"	"	15	0.15	6.9		100	94	79	50	36	29	23	17	12	9.3	2.20	96

Notes:

1. Asphalt content was determined by California Test 362 except for the control mix which was determined by California Test 310.

2. Relative compaction is based on laboratory maximum densities from street samples.

(last paragraph, Section E), asphalt content will not be discussed in detail due to extraction problems.

- Passing No. 200 Fraction: The specification called for an allowable range of 3-8%. This was the only grading size that was consistently out. It ranged from 7.9 to 9.5% with only one of 16 samples within specifications.

- Relative Compaction: The mixes ranged from 95 to 101%. The high values can probably be explained by relatively high mix temperatures (above 300°F) and a high passing No. 200 fraction.

Based on Table 10, the following comments can be made concerning the first lift:

- Lift thickness: The lift ranged from 0.08 to 0.14 ft with an average of about 0.11 ft. This also shows good paving control.

- Asphalt Content: Overall, it appears the asphalt content was close to the design values except for the Ramflex rubber mix which was about 0.6% low and, therefore, out of specifications ($\pm$0.5%). However, the same comment applies here on extraction results that was made for the final lift.

- Passing No. 200 fraction: The same comments can be made here as were made for the final lift, except the range was from 7.4 to 11.8%.

- Relative Compaction: The same comments can be made here as were made for the final lift, except the range was from 95 to 102.

H. Summary of Field Installation

The project chosen for the placement of these modified mixes should provide an excellent opportunity to study the performance of these products in a severe thermal environment and under fairly heavy tire chain action.

APPENDIX B

Construction Correspondence

Even though there were some problems during mixing and placement, in general the mixes looked very good and were well compacted (good relative compaction). Whether the problem with the high passing No. 200 fraction (bag house dust) or the apparent variation in asphalt content will have a significant effect on the performance of these mixes is difficult to answer. Nevertheless, they will receive a rigorous trial which should provide some answers as to their effectiveness in resisting surface abrasion and/or reflection cracking.

VIII. PERFORMANCE MONITORING

The test sections will be monitored for a minimum of five years and a performance survey will be conducted at least annually. Pavement cores will be obtained as necessary to aid in this evaluation.

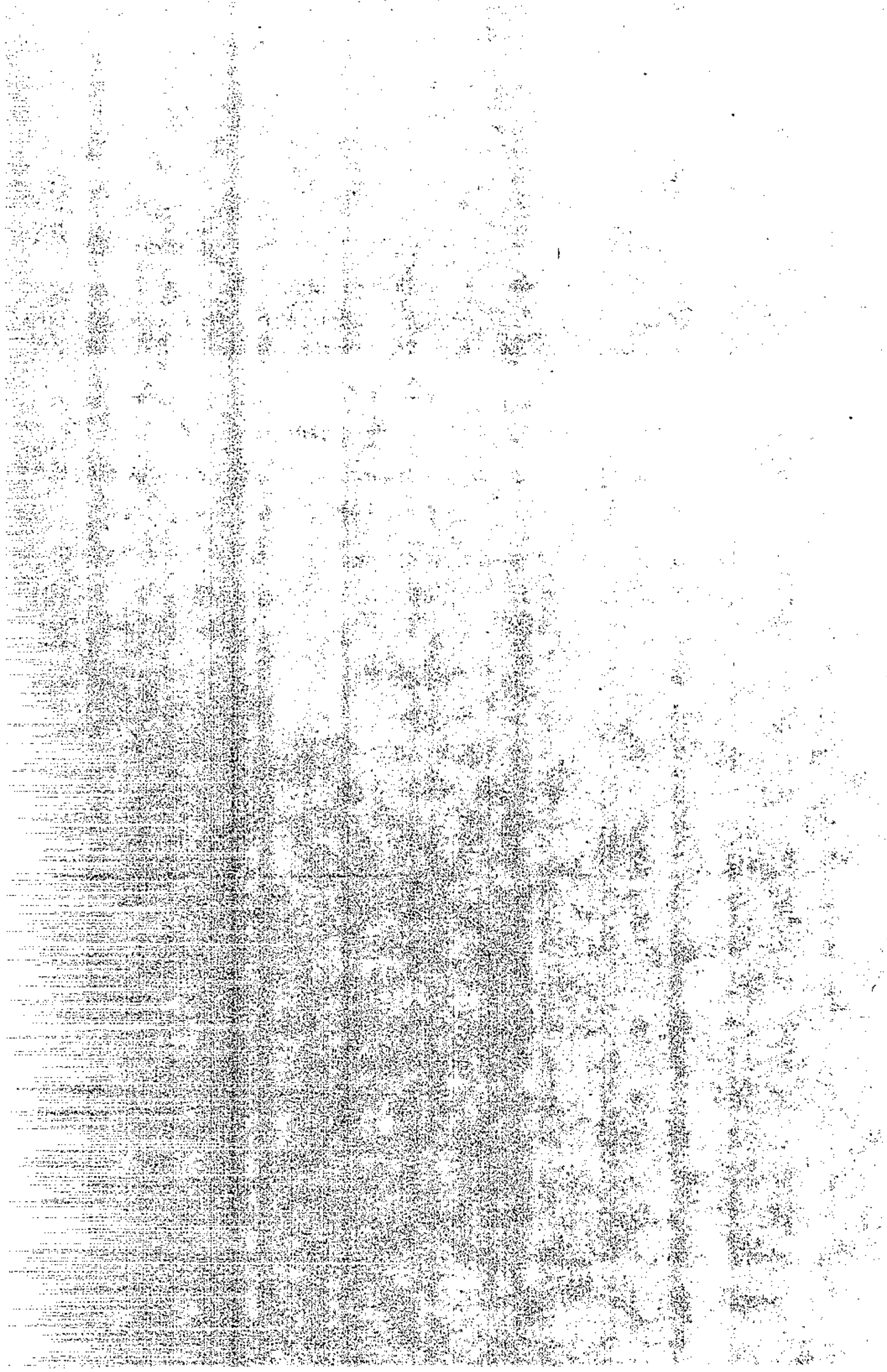
The first performance survey was made in April 1985, after one winter of service. To date the test sections, and the control are performing extremely well with only some minor pitting and slight raveling in the transition areas between test sections.

A copy of the survey is found in Appendix F.

IX REFERENCES

(1) Smith, R.D., "Experimental AC Overlays of PCC Pavement," California Department of Transportation, CA/TL-83/07, November 1983.

(2) de Laubenfels, L., "Effectiveness of Rubberized Asphalt in Stopping Reflection Cracking of Asphalt Concrete" (Interim Report), California Department of Transportation, FHWA/CA/TL-85/09, January 1985.



APPENDIX A

Product Evaluation Test Data

TABLE A

PRODUCT EVALUATION TEST DATA
(AGGREGATE B[1])

ADDITIVE	ASPHALT CONTENT (%)	M_r (PSI x 10^5)	STABILITY	SPECIFIC GRAVITY	VOIDS (%)	COHESION
CONTROL (Conv. Mix)	7.1	4.15	36	2.23	8.5	120
	7.4	4.91	37	2.25	6.8	130
Ramflex (1.0%)[2] Crumb Rubber	7.4	12.00	28	2.24	7.4	150
	7.9	5.75	17	2.28	5.0	254
	8.2	3.34	23	2.28	4.6	335
	8.4	4.60	22	2.26	5.2	235
	8.9	4.60	13	2.29	3.2	300
BoniFibers (0.25%)	7.6	16.00	35	2.25	6.7	245
	7.9	11.00	39	2.27	5.5	275
	8.2	7.09	36	2.26	5.4	250
Fiber Pave 3010 (0.3%)	7.4	5.66	39	2.22	8.2	173
	7.6	9.36	35	2.25	6.7	195
	7.9	9.38	34	2.23	7.0	235
	8.2	6.65	36	2.26	5.4	330
Marvess Olefin (0.4%) (60 Den.)	7.6	6.20	35	2.27	6.0	205
	7.9	6.50	35	2.25	6.3	230
	8.2	6.78	33	2.25	6.0	230
Marvess Olefin (0.4%) (16 Den.)	7.1	3.29	32	2.18	10.4	120
	7.6	3.31	32	2.20	8.8	175
	7.9	3.50	39	2.20	8.3	142
	8.1	3.22	28	2.24	6.5	165
	8.6	3.18	30	2.25	5.8	225
G-274 (1%) Crumb Rubber	7.4	4.42	26	2.22	8.2	168
	7.9	4.04	24	2.23	7.1	185
	8.2	2.91	23	2.24	6.2	212
	8.4	5.53	18	2.24	6.0	195
	8.9	4.70	14	2.26	4.3	275

TABLE A (Continued)

PRODUCT EVALUATION TEST DATA
(AGGREGATE B[1])

ADDITIVE	ASPHALT CONTENT (%)	M_r (PSI x 10^5)	STABILITY	SPECIFIC GRAVITY	VOIDS (%)	COHESION
ARS[3]	7.4[3]	1.21	32	2.19	8.5	125
(Arm-R-Shield)	7.9	1.55	31	2.21	8.0	235
	8.2	0.95	30	2.18	8.7	141
	8.4	1.35	24	2.25	5.5	295
	8.9	2.01	30	2.24	5.2	340
PlusRide	7.5 (11.0)[4]	4.33	12	2.19	5.2	135
	8.0 (10.0)	1.89	9	2.16	6.1	60
	8.5 (9.0)	2.57	2	2.22	3.1	56

Notes:
1. 1/2" maximum medium Type A.
2. All percentages are by dry weight of aggregate.
3. This mix used a binder which contained 76% asphalt, 20% rubber, and 4% extender oil. (All 5 samples.)
4. The number in parenthesis is the percent of material passing the No. 200 sieve.

APPENDIX B

Construction Correspondence